JANSKY & BAILEY SYSTEMS ENGINEERING DEPARTMENT

TR-PL-9037

Final Report

TECHNICAL AND COST FACTORS THAT EFFECT TELEVISION RECEPTION FROM A SYCHRONOUS SATELLITE

Submitted to

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Washington, D.C.

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June 30, 1966

ATLANTIC RESEARCH

Correction for

Final Report

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A SYNCHRONOUS SATELLITE

Dated: June 30, 1966 TR-PL-9037

Please change Noise Figure of ERP's 90, 80, 70, and 60 on page 109 to each read 2.0.

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JANSKY & BAILEY ALEXANDRIA, VA.

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FOREWARD

This report has been prepared by the Jansky and Bailey Systems Engineering Department of Atlantic Research Corporation under Contract No. NASW - 1305 to the Communication and Navigation Program Office of the National Aeronautics and Space Administration, Washington, D. C.

Its purpose is to provide the National Aeronautics and Space Administration with an evaluation of the technical factors that affect the feasibility and cost of television reception from synchronous satellites.

The technique of analysis used in this report has been developed in such a way that the evaluation can be updated to take account of new data relative to technology and environmental effects as such become available. This updating will be particularly important in respect to updating of cost information in new areas of technology and in the introduction of data on environmental effects as new data is developed from experience and experiments. Two particularly important areas upon which better environmental data is required are (1) the values of indigenous noise in various types of receiving station environments and (2) the specific effect of the ionosphere on limiting the bandwidth of signals that can be effectively transmitted on frequencies below 1,000 Mc/s.

The engineers of Jansky and Bailey Systems Engineering Department are extremely grateful for the cooperation and help received from members of government and industry who were contacted for various types of information and data needed in the course of this study. Particular appreciation is extended to Mr. A. M. Greg Andrus of NASA Headquarters under whose personal direction this project was formulated and whose guidance, encouragement, and constructive criticism have been a valuable part of a team effort throughout the conduct of the work.

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1.0 INTRODUCTION

1.1 GENERAL

In August 1965, the Communication and Navigation Program Office of the National Aeronautics and Space Administration contracted with the Jansky & Bailey Systems Engineering Department of Atlantic Research Corporation to perform a study to investigate all factors that affect the cost and quality of reception of television material transmitted via satellites. The results of this study are presented in this report. In it an evaluation is made of factors effecting cost and quality of reception as a function of effective radiated power from a synchronous satellite. In particular this study specifies the technical requirements for providing television video of defined grades of quality and considers all combinations of equipment that will provide satisfactory reception.

A large range of different values of ERP (Effective Radiated Power) are assumed and a specific determination is made of minimum cost receiving system parameters for each assumed value of satellite ERP. A separate set of solutions is derived for operation in different parts of the frequency spectrum from 200 Mc/s to 12,000 Mc/s. Thus, the results include combinations of receiving stations' parameters that range from low cost installations, such as would be reasonable for home type installations using high satellite ERP, to more expensive receiving installations such as might be more appropriate for specialized stations that would serve terrestial (land based) distribution systems using low values of satellite ERP. Cost and performance information has been obtained for components which can be provided between the present and 1970 provided a requirement is established. Information has been developed on a component by component basis and the costs of alternative feasible receiving system combinations have been derived. This has provided a broader basis for comparison than would be possible had the evaluation been limited to a combination of complete systems proposed by various suppliers.

A computer program utilizing the IBM 360-30 system was used to facilitate determination of a minimum cost receiving system from all possible combinations of receiving system parameters. The body of this study will explain the rationale used in optimization of system parameters for various values of assumed satellite power and for operation in different parts of the spectrum. A detailed explanation will be provided as to the development of the information which was fed to the computer. An analysis will be given of the results obtained.

1.2 SPECIFIC PROBLEM LIMITS

To perform a completely exhaustive analysis of the stated problem area is, at best, difficult. However, a meaningful analysis is possible provided certain practical limitations are recognized. Therefore, the assumptions underlying this study may be stated categorically as follows:

(a) The frequency range of detailed investigation is limited to the range 200 Mc/s through 12,000 Mc/s. Propagation and technological limitations preclude realistic consideration of frequencies outside this band. At the lower end of this band cosmic noise and indigenous noise become severe problems, and it is difficult to obtain appreciable gain with economic antenna structures. Above 12,000 Mc/s the technology is presently not well developed and atmosphereic attenuation begins to become a serious problem.

(b) The satellite considered is in a synchronous equatorial orbit. and has an ERP ranging from 30 dbw to 90 dbw. Its look angle from receiving status is assumed to be 43°. Results using this look angle illustrate the importance of taking into account a specific look angle or range of look angles in design of antenna to suppress indigenous noise.

(c) Receiving stations will exist in quantities between one and a million depending upon cost and demand. For the purpose of this study concentration may be limited to an analysis of those components of a receiving station that directly affect the solution of the one-way transmission equation. These are referred to as primary components to distinguish them from those components that do not affect transmission system requirements. <u>This study considers only the cost and performance of those system components that fall in the primary category</u>.

(d) The specific types of components which are available as possible primary components are: yagi and parabolic antennas of all sizes, germanium-arsenide, silicon and tunnel diodes, parametric amplifiers in all modes, pre-amplifiers using transistors, waveguide, coaxial cable and twin lead feed line, mixers, circulators, and horn and dipole feeds for parabolas. In general, knowledge of the technology that will apply to these types of system components is well defined through the time period 1970, and projections of available costs and performance specifications are reliable for comparative analyses. However, extrapolation beyond 1970 is not realistic. The cost of primary equipment installation is not included since this varies from actual system to actual system and may include numerous variables which would not make the study conducive to comparative analyses.

(e) The analysis of the minimum cost receiving station includes information, based on the most recent research, on ionospheric and atmospheric propagation losses, attenuation in signal level due to rain and clouds, Faraday rotation of the electromagnetic field, and noise contributions from the earth, sun, radio stars, and other discrete sources.

(f) The primary source of information for indigenous noise, one of the most important factors in the receiving system environment, is the ITT Communications Handbook. This is an important limitation of the study since the pertinent information is based upon measurements made almost thirty years ago. Also, the available information had to be extrapolated to cover the entire frequency range of interest. To minimize the effect of this limitation, results are determined for several values of indigenous noise ranging from a maximum value derived from interpretation of the ITT Handbook data to a minimum value corresponding to no indigenous noise. A 40 db range of values has been considered in this report the maximum value being assumed to be applicable to highly concentrated urban areas.

(g) The required S/N at the receiver output is assumed to be 40 db. With this magnitude of signal present the viewer would have a good-to-excellent picture. The information bandwidth is assumed to be 4 Mc/s in accordance with the television transmission standards of the U.S.A.; the type of modulation is assumed to be either FM (standard or feedback) or AM-VSB. Curves for adjusting the results for other values of required output quality are also included.

(h) This study assumes that ionospheric transmission bandwidth is sufficient to permit use of the optimum modulation technique at all frequencies considered. Several investigators have theorized on the dispersive effects of the ionosphere on the amount of basebandwidth available for information transmission as a function of frequency. Most of the analyses have considered the effects of PCM. The only commentator on FM, Staras, considered systems with bandwidths more than twice those determined to be the optimum for systems specified in this study. Thus, there is not a sound basis for making valid judgements as to the adequacy of ionospheric transmission bandwidth as a function of frequency and modulation type. However, there is good evidence that no problem exists with respect to operation of frequencies above 1,000 Mc/s. More important, there are indications that bandwidth limitation will occur for transmission on frequencies below 1,000 Mc/s. Staras refers to a degradation associated with FM having twice the bandwidth considered optimum for systems specified in this study. Unfortunately, no data is available for the exact conditions specified as optimum herein. To minimize the effect of this limitation on the use of the results of this study, cost information has been provided for both AM-VSB and FM modes of operation on frequencies below 1,000 Mc/s.

1.3 GENERAL APPROACH

The analytical model which was used to achieve the purposes of this study, as outlined in the previous section, is a fairly rigorous version of the one-way propagation equation which was developed specifically for the satellite TV problem. In effect it relates all the factors which determine the magnitude of the output signal-to-noise ratio of a receiving station. These factors may be divided into three categories: (1) system design constants (modulation improvement, satellite ERP, required quality of signal), (2) environmental effects (atmospheric, ionospheric attenuation, indigenous noise), and (3) primary equipment performance characteristics and costs (antenna gain, noise figure, feed line loss).

Cost and performance information relative to the primary equipment components was obtained through extensive consultations with engineers and scientists associated with the testing and development of the pertinent devices. In all cases an investigation was made to obtain reliable information for establishing the cost of these devices in quantities ranging between one and a million. Where the technology for mass production was fully developed as with broadcast type television receiver components, it was possible to do this easily. However, there were some areas in which this was not possible, such as mixers, circulators, parabolic antennas. Those items are not now mass produced; therefore, it was possible to obtain accurate information only on small quantities. In such cases appropriate learning curves were applied to determine the cost per unit for large quantities. The technique of applying learning curves to extrapolate costs from small quantities of new devices to large quantities of mass produced items is well established and is generally used with considerable confidence for fixed price competitive bidding.

1.4 SUMMARY OF RESULTS

In the main body of the report cost versus ERP curves are presented for various combinations of frequency, indigenous noise, and quantities of receivers. Correction factor curves are presented adjusting the results to apply to other characteristics of operation than those used in the study for comparative analyses.

The extensive cost information presented in Section 4.0 of this report is summarized in Figures 1.4.1 through 1.4.6. Figure 1.4.1 shows cost versus frequency for various ERP's and the receiver located in a large city. It shows very clearly, that for a given ERP, the most advantageous frequencies from a minimum cost standpoint are from 800 to 1,000 Mc/s. In general, cost rises sharply below 600 Mc/s and also increases appreciably about 1.0 Gc/s. The band from 600 Mc/s to 1.0 Gc/s is advantageous for both environmental and equipment reasons. Below 600 Mc/s, indigenous and cosmic noise introduce a high system noise level which must be compensated for by larger antennas. Above 1.0 Gc/s, equipment becomes expensive, while in the 600 Mc/s to 1.0 Gc/s band, present UHF tuner techniques are applicable. For the case of 90 dbw satellite power the cost does not increase at the lower frequencies. This is because with this extremely high power, the noise level is adequately exceeded even with the cheapest possible receiver configuration.

Figure 1.4.2 shows the same type curves as Figure 1.4.1, at an assumed remote rural location where indigenous noise is zero. This would be an extreme case since in general even rural areas encounter some indigenous noise. The main difference is that the cost for operation below 1.0 Gc/s is less for rural locations. However, at low values of ERP the cost increases with reduced frequency because the noise level established by the cosmic noise establishes a requirement for a large antenna and in some cases a different modulation system than vestigial sideband.

Figure 1.4.3 gives the ERP as a function of frequency, which will allow a certain receiving system with a certain cost to be

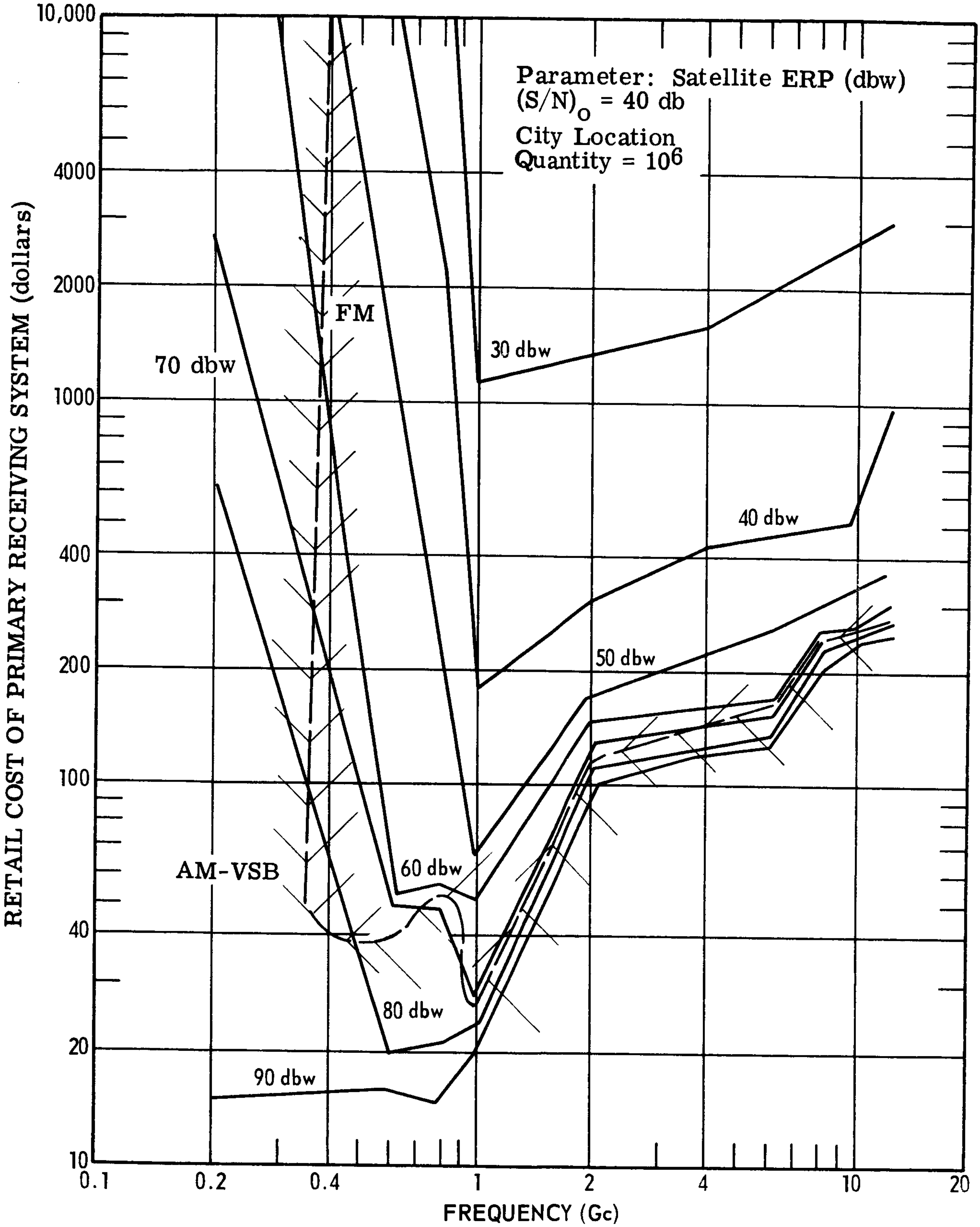

Figure 1.4.1. Retail Cost of Primary Receiving Systems Versus Frequency - Maximum Indigenous Noise.

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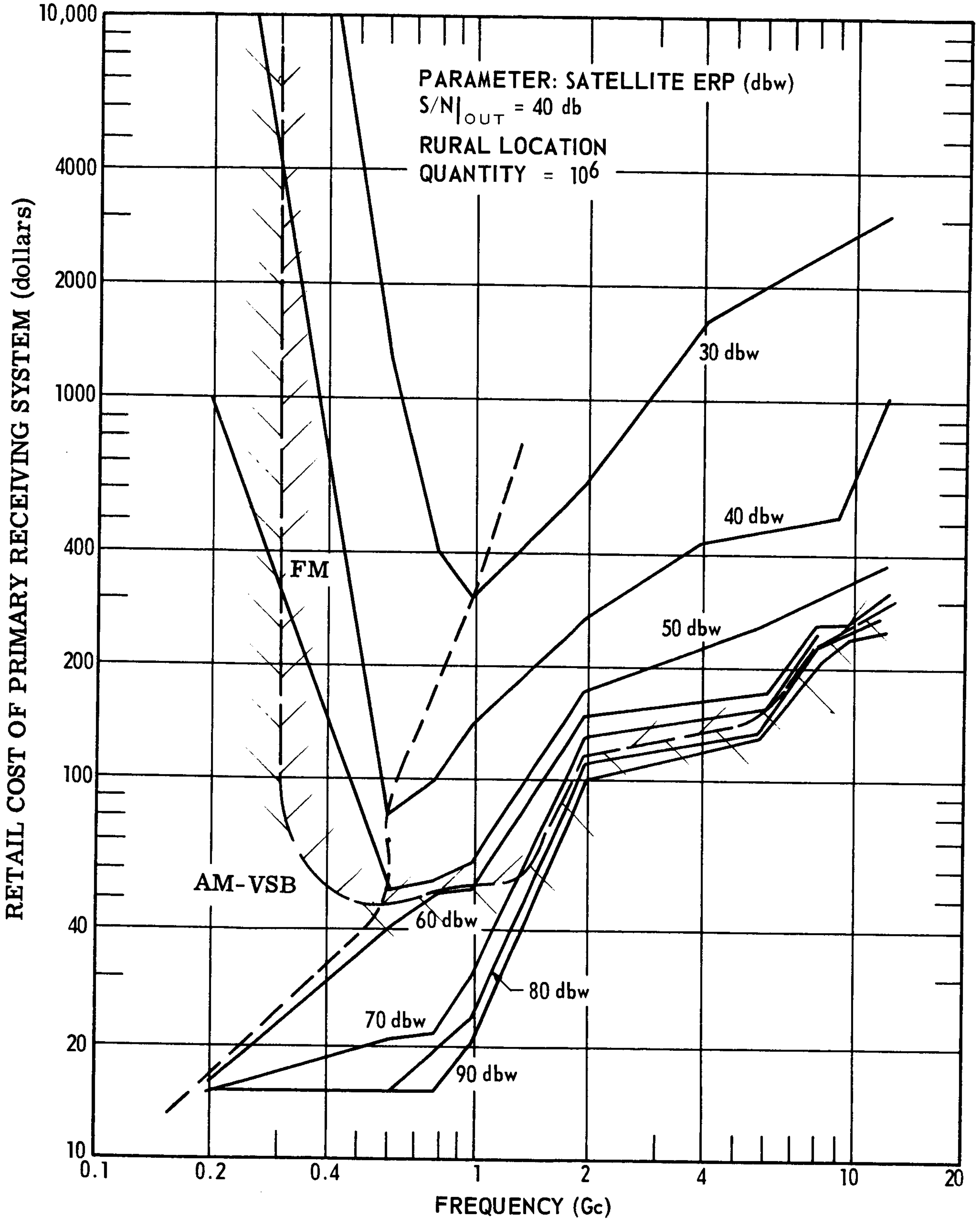

Figure 1.4.2. Retail Cost of Primary Receiving Systems Versus Frequency - Minimum Indigenous Noise.

satisfactory. For a cost of $40 a very high ERP is required. Beyond 1.0 Gc/s a higher cost system is required for the range of ERP's which are considered. Below 1.0 Gc/s, higher cost receiving systems do not allow for much lower ERP. This is due to cost of antennas which will suppress the indigenous noise and allow a satisfactory $(S/N)_o$ at the reduced ERP's. Above 1.0 Gc/s, a higher increase in antenna gain can be obtained with a certain price increase than can be obtained at the lower frequencies. An increase in receiving system cost can then reduce the required ERP significantly.

The effect on receiver cost due to changes in the standard of operation is shown in Figure 1.4.4 for a city location and quantities of one and 10^6. The computations made in the body of the report were for a $(S/N)_o$ of 40 db. The $(S/N)_o = 40$ db curves are shown along with curves for $(S/N)_o$ corresponding to specific grades of service. Grade 1 is a picture of exceptional quality and no noticeable interference. Grade 2 is for a good picture with slight interference and Grade 3 is a passable picture. At a certain point on the curves, the minimum cost system configuration changes from vestigial sideband modulation to frequency modulation. VSB is used for all systems above this point while FM is used for all systems for an ERP less than the breakpoint value. The deviation in required ERP for the VSB systems is greater than the deviation for the FM systems. The change in ERP is equal to the change in $(S/N)_o$ for VSB systems, while the change in required ERP in db is approximately 25 per cent of the change in $(S/N)_o$ for FM systems. This is due to the fact that in VSB systems, a change in $(S/N)_o$ must be directly compensated for in ERP, while in an FM system, a change in

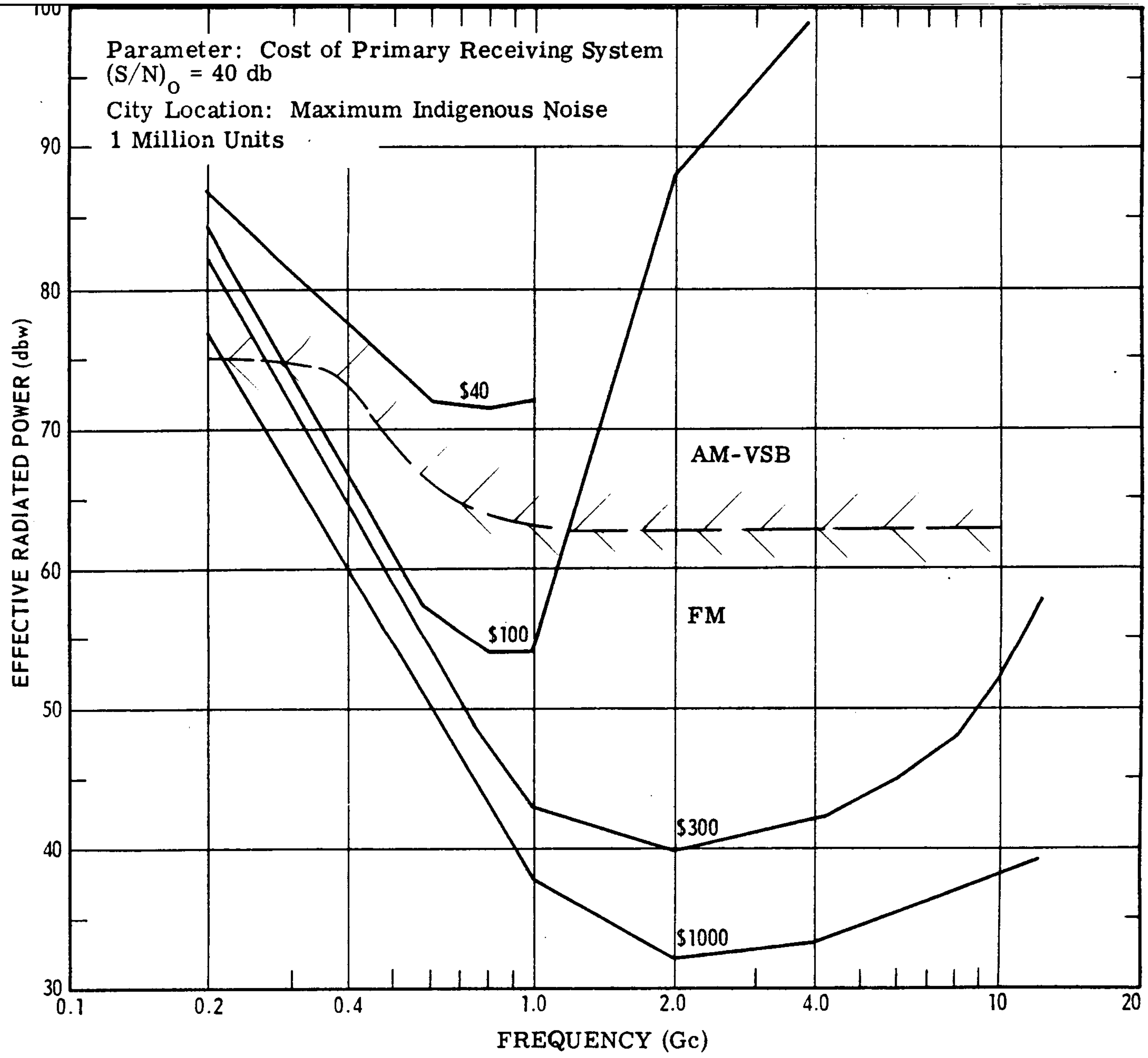

Figure 1.4.3. ERP Versus Frequency for Receiving Systems with a Specific Cost.

$(S/N)_o$ will also change the modulation improvement factor. The necessary correction for FM systems is discussed fully in Section 4.0.

The effect of indigenous noise on the system cost is also shown in Figure 1.4.4. The difference in cost between city (high noise) and rural (no indigenous noise) locations can be obtained from the curves for Grade 3 service and $n = 10^6$.

As can be seen, the presence of indigenous noise increases the system cost by a factor of 4.0 at the lower ERP's. The data shown in Figure 1.4.4 are the minimum cost system at each ERP considering all frequencies.

Figure 1.4.5 illustrates the change in receiving system cost due to indigenous noise at 600 Mc/s for quantities of one and 10^6. It is seen that the difference between the no I.N. (indigenous noise) case and maximum I.N. case increases as ERP is reduced. This is due to the fact that as ERP is reduced, it becomes necessary to reduce the system noise level which leads to a requirement for a high gain antenna. As the gain in the antenna main beam is increased, the antenna sidelobes are reduced and the indigenous noise is reduced.

The system noise level is made up of contributions from indigenous, cosmic, and receiver noise. As the satellite ERP is reduced, a larger antenna becomes necessary for two reasons. The first reason is to provide enough signal at the receiver terminal and the second is to suppress the indigenous noise contribution to the overall system noise level.

There is no direct correspondence between the change in required satellite ERP and the different cases of indigenous noise. It depends

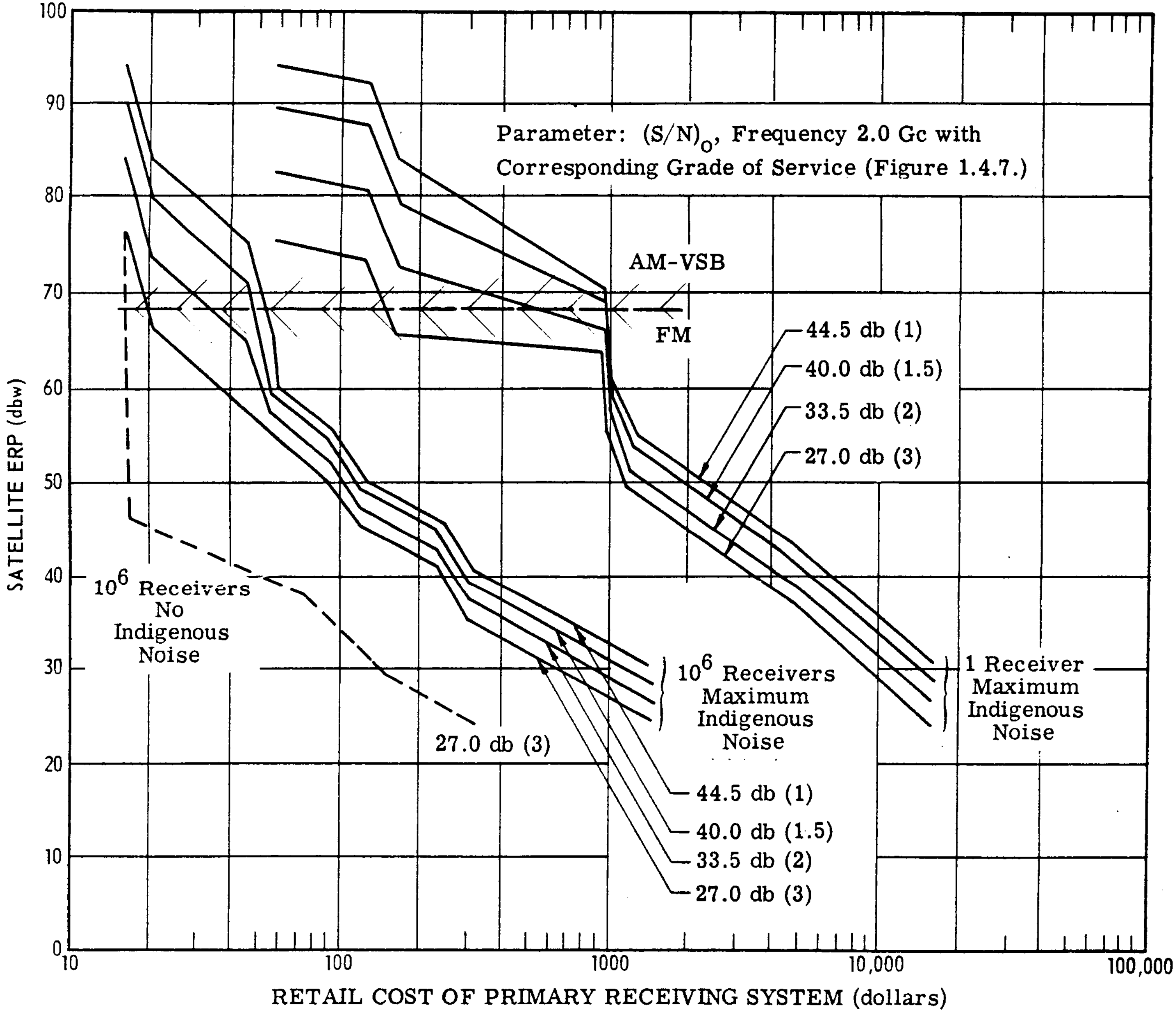

Figure 1.4.4. ERP Versus Cost and Grade of Service.

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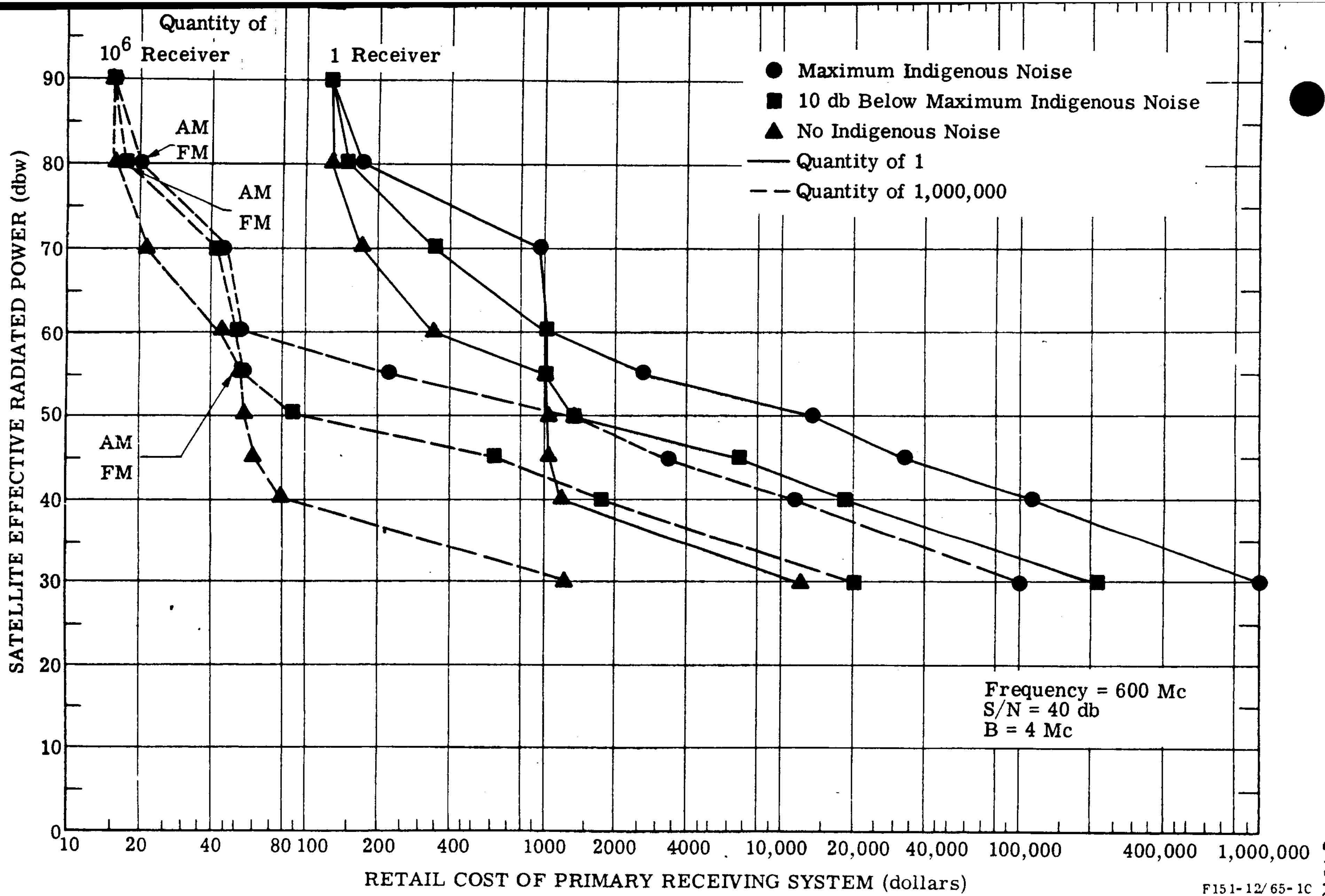

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Figure 1.4.5. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 600 Mc, for Different Values of Indigenous Noise.

upon the percentage of the total noise level which is attributable to the indigenous noise.

The variation in cost resulting from quantity variation is also seen in Figure 1.4.5. A change in quantity of 10^6 changes the cost per system by a factor of 10. If the curves for quantities of 10^2 and 10^4 were placed on the Figure, there would be equal spacing between the curves for the four different quantities. For a change in quantity of 100 times, the associated cost is reduced by a factor of .59.

Figure 1.4.6 shows the cost of receiving systems as a function of $(S/N)_o$ for various satellite ERP's.

Figure 1.4.7 shows the descriptions of the various grades of service and the S/N (db) required at the output of a receiver where conventional television, which uses AM-VSB, is employed. It is important to recognize that there is a difference of 17 db or a ratio of 50 times in power requirement for excellent quality over that required for passable quality. When FM modulation is used instead of AM-VSB, the corresponding ratios are approximately 8 db less as will be discussed further in later sections of this report.

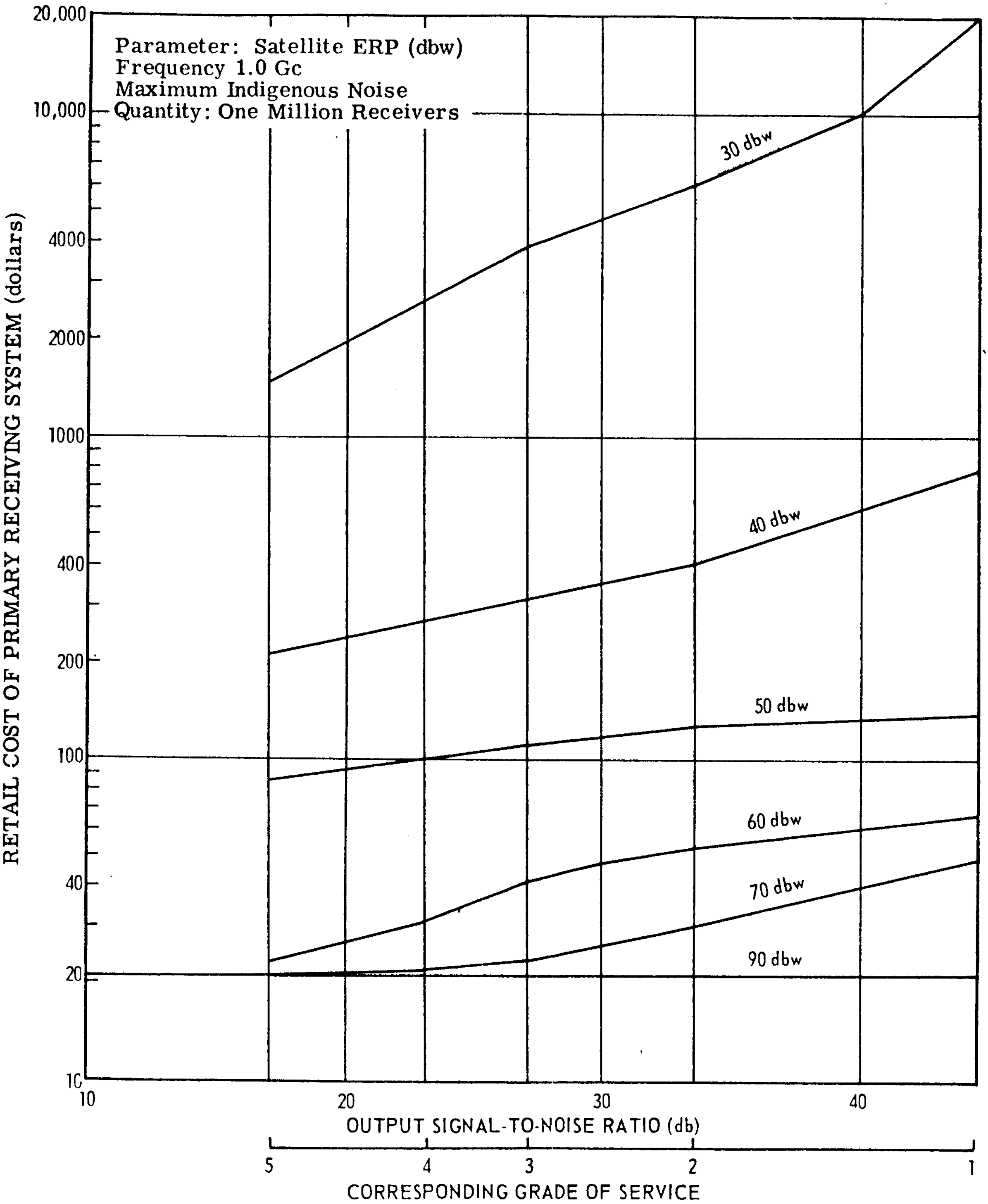

Figure 1.4.6. Retail Cost Versus Desired Grade of Service of Minimum Cost Receiving Systems at 1.0 Gc.

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SIGNAL GRADE	DESCRIPTION	MEDIAN OBSERVER S/N (db)
1	EXCELLENT; PICTURE OF EXTREMELY HIGH QUALITY	44.5
2	FINE; HIGH QUALITY; INTERFERENCE PERCEPTIBLE	33.5
3	PASSABLE; ACCEPTABLE QUALITY INTERFERENCE NOT OBJECTIONABLE	27.0
4	MARGINAL; POOR QUALITY; INTERFERENCE SOMEWHAT OBJECTIONABLE	23.0
5	INFERIOR; VERY POOR QUALITY; OBJECTIONABLE INTERFERENCE PRESENT	17.0
6	UNUSABLE; SO BAD COULD NOT WATCH IT	—

*A S/N OF 40 db WAS USED AS A REPRESENTATIVE VALUE IN THIS STUDY.

Figure 1.4.7. Quality of Picture Versus Receiver (S/N)
(Based on New York City UHF TV Study).^{o*}

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2.0 ANALYTICAL MODEL

2.1 GENERAL

As mentioned in the introduction, before the cost of the receiving station can be determined the system equation, which relates the environmental parameters, the hardware parameters and the operational requirements, must be established. In developing the general equation, the coordinate system shown in Figure 2.2.1 and the model shown in Figure 2.3.1 have been used. All factors which contribute to the system equation for the frequency range 100 $Mc \leq f \leq$ 12 Gc are represented. The general system equation will be developed and will be simplified by eliminating those factors having negligible influence. Each of the system factors is then discussed and evaluated in detail.

2.2 COORDINATE SYSTEM

In the development of the systems equation, a spherical coordinate system will be used. The general coordinate system is shown in Figure 2.2.1. The center of the system is the receiver location with X in the direction of increasing longitude and constant latitude and Y in the direction of increasing latitude and constant longitude. Of principal interest in this study is the angle from the normal, θ. A particular θ of interest is the angle to the line of sight with the satellite. This will be called θs. This θs can be determined from the coordinate system geometry as a function of latitude and relative longitude. Relative longitude is determined as the longitudinal separation of the receiver position and the satellite fix. θs is given as a function of the latitude and relative longitude in Figure 2.2.2.

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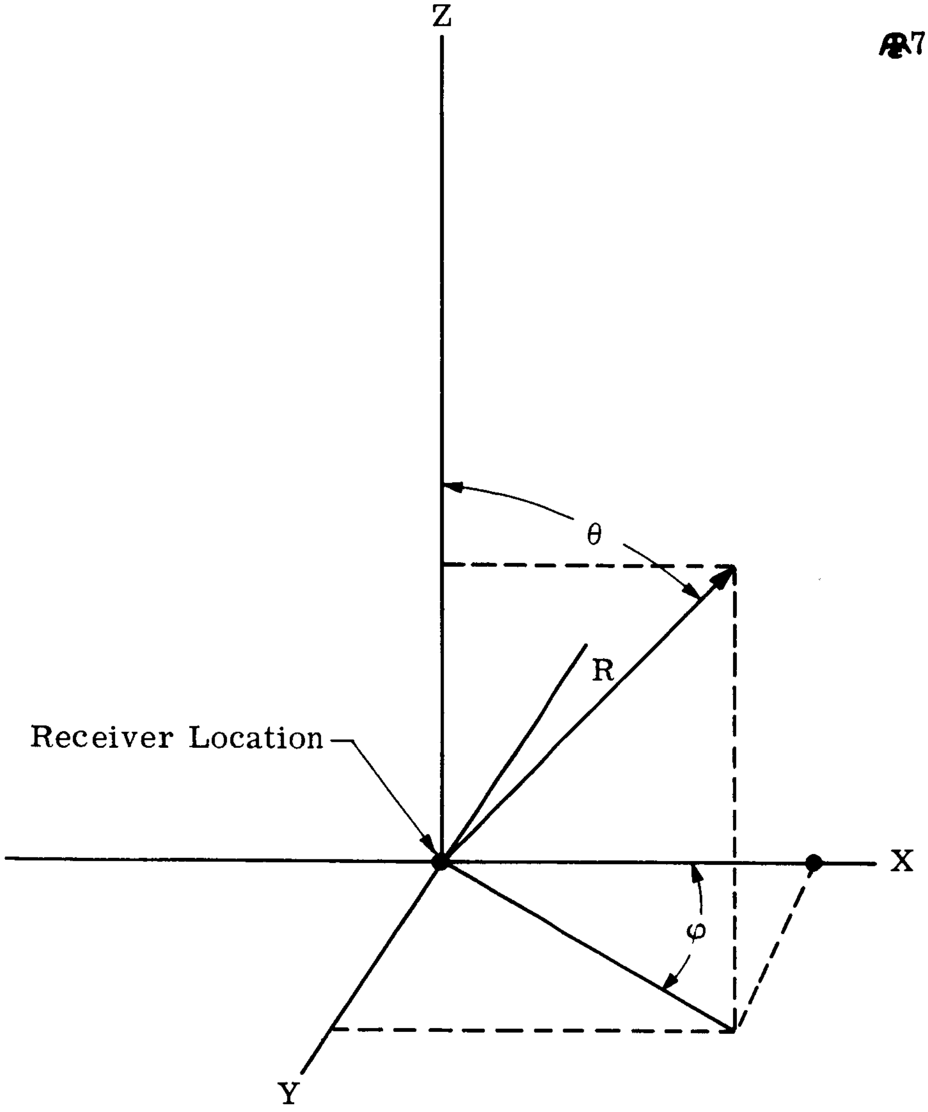

X - Y Plane is Tangent to the Earth's Surface

X is Longitude

Y is Latitude

Z is Normal to the Earth's Surface

Figure 2.2.1. General Coordinate System.

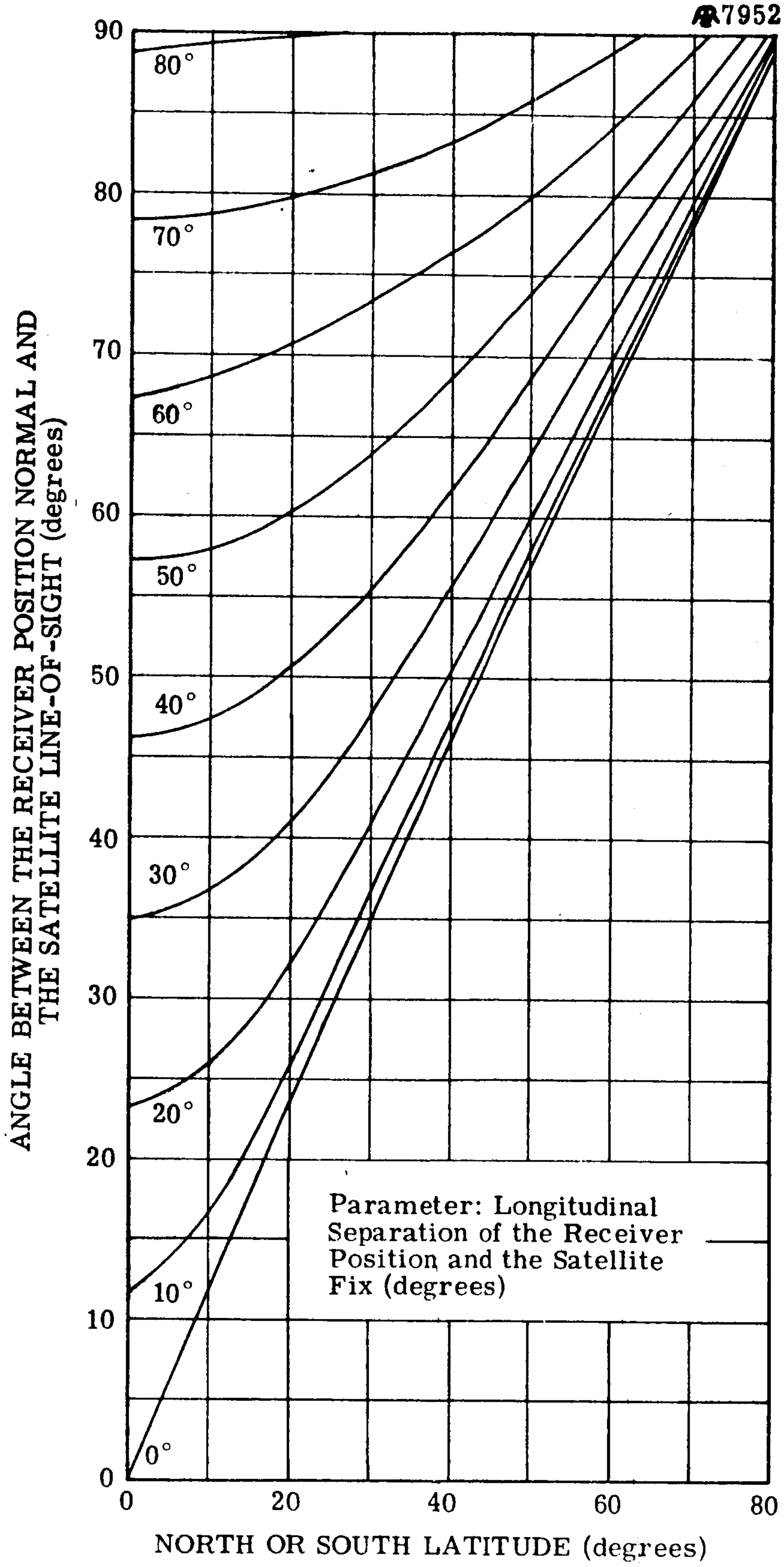

Figure 2.2.2. θ_s as a Function of Latitude and Relative Longitude.

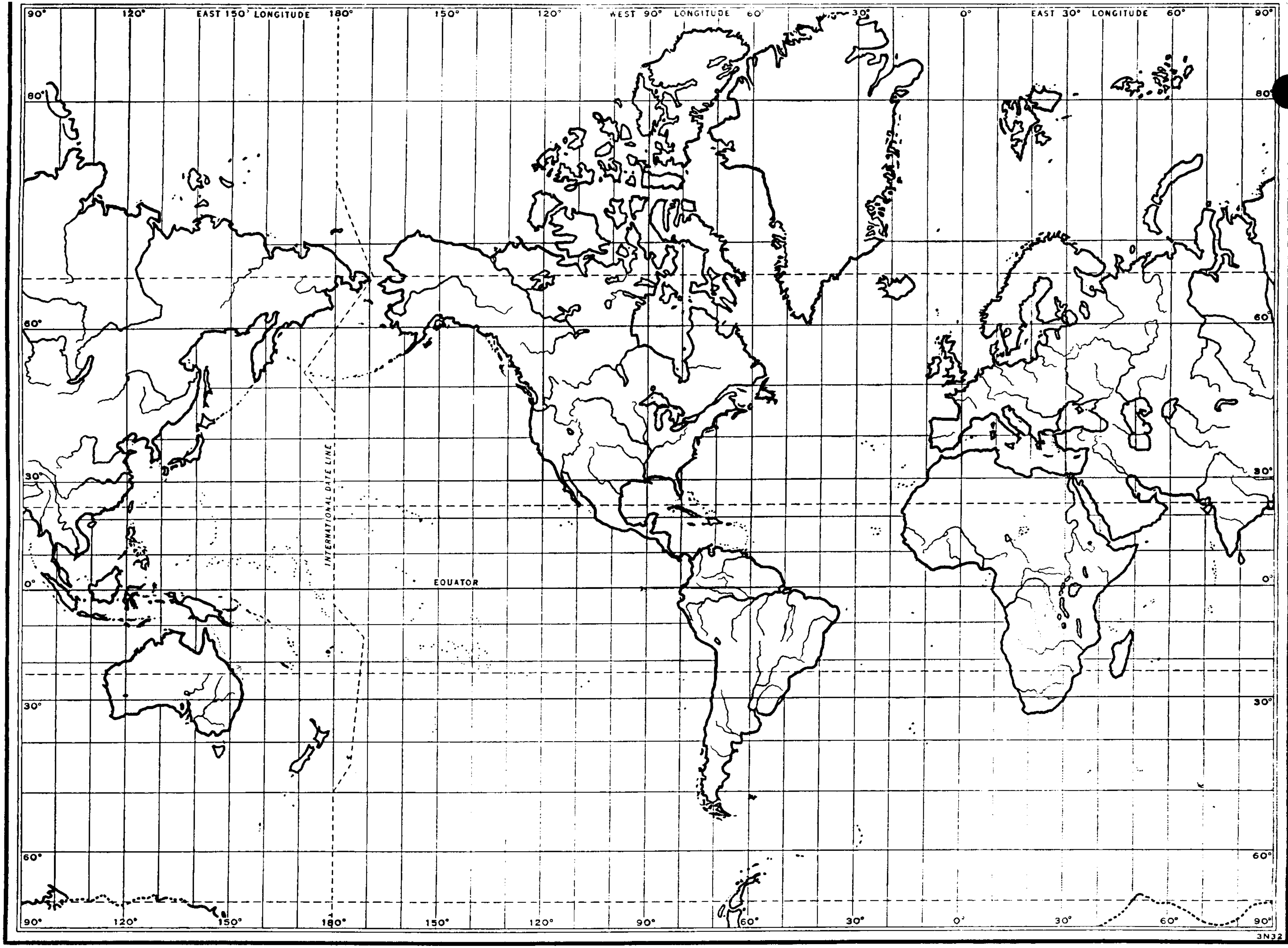

Figure 2.2.3. World Map.

The angle θ_s is an important parameter since many of the environmental factors which enter the system model are functions of θ_s. With the use of the world map shown in Figure 2.2.3, θ_s can be determined for any position in the world. It should be kept in mind that the antenna elevation angle is $90° - \theta_s$.

2.3 SYSTEM EQUATION

Figure 2.3.1 shows in a pictorial sense the various parameters which will influence system operation. The symbols shown in Figure 2.3.1 which have not been defined previously are defined below:

T_{CK} = effective background cosmic noise

T_{D_i} = effective brightness temperature of the ith discrete radio noise source

T_{ION} = ambient temperature of the ionosphere

T_{atm} = ambient temperature of the atmosphere

T_g = ambient temperature of the earth

T_{RF} = ambient temperature of the receiver RF components

T_r = ambient temperature of the rain and clouds

α = [1]normalized percentage of the energy passing through the ionosphere which is absorbed by the ionosphere

β = [1]normalized percentage of the energy passing through the atmosphere which is absorbed by the atmosphere

L = [1]normalized percentage of the energy passing through the feeder line which is absorbed by the feeder line

Q_N = [1]normalized percentage of the energy passing through rain in the vertical direction which is absorbed by rain

Q_H = [1]normalized percentage of the energy passing through the rain in the horizontal direction that is absorbed by rain

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[1]Normalized percentage is a ratio or the fraction of the energy absorbed or lost where 1.0 represents total energy otherwise available.

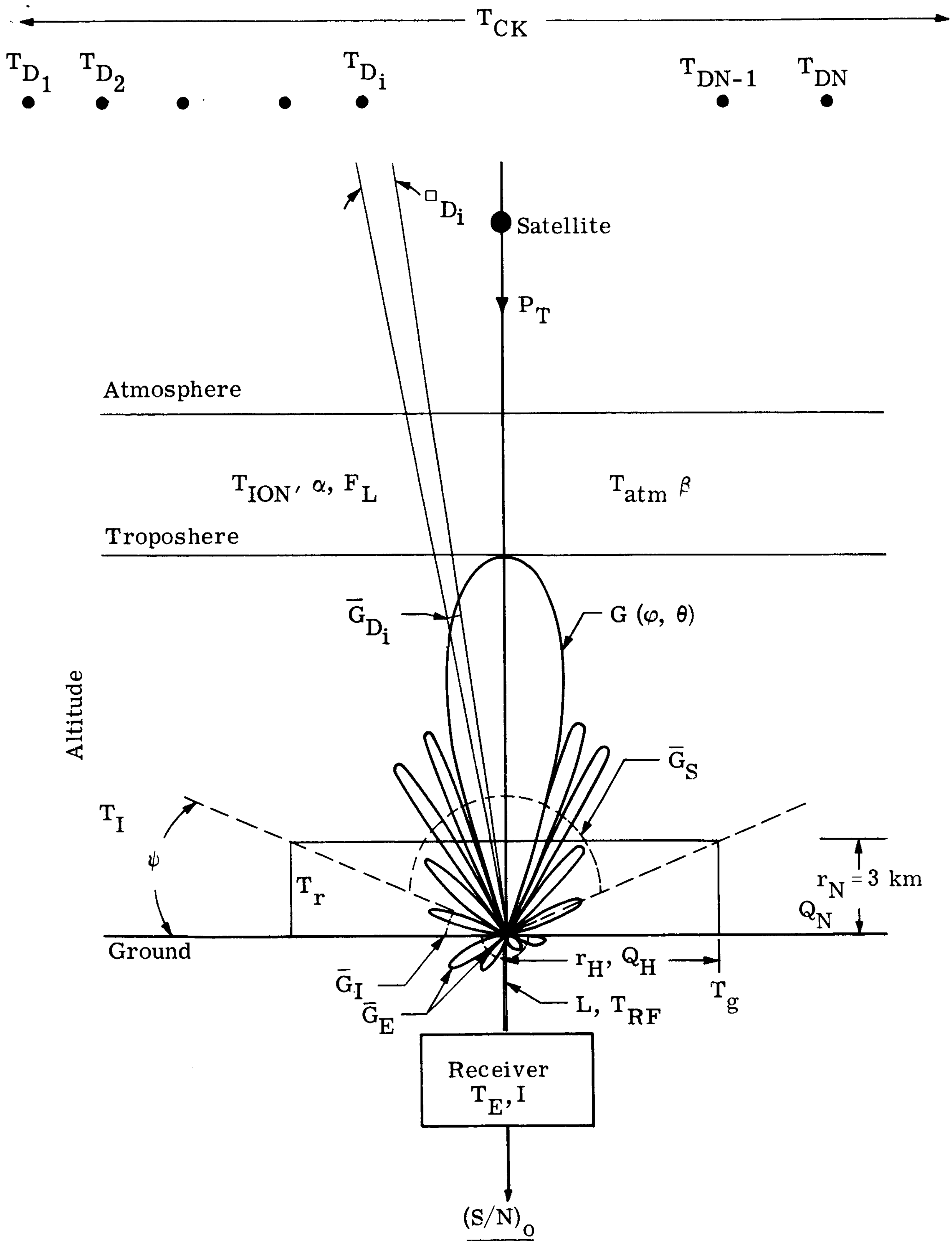

Figure 2.3.1. Environmental Model for a Ground Receiver.

r_N = length of the rain in the normal direction

σ = $1-N_K$ = antenna radiation loss (ohmic)

N_K = antenna radiation efficiency

r_H = length of the rain in the horizontal direction from the receiver

F = receiver noise figure

T_E = receiver noise temperature = $(F-1)290$

F_L = [1]normalized percentage of energy loss due to polarization mismatch of the satellite and receiving antennas caused by Faraday rotation occurring in the ionosphere

T_I = effective brightness temperature associated with indigenous and interfering noise sources

ψ = angle above the horizontal within which the antenna sees T_I

$\square D_i$ = angle subtended by the ith discrete source

$G(\varphi,\theta)$ = antenna gain in the direction determined by φ and θ

$\overline{G}_I$ = average antenna gain over the solid angle determined by $-90° + \psi < \theta \leq 90° - \psi$ $-\pi \leq \theta \leq \pi$, which is a sector near the horizon that accepts indigenous noise

$\overline{G}_S$ = average gain over the front half of the antenna, which is the region that accepts sky noise

$\overline{G}_E$ = average gain over the back half of the antenna, which is the region that accepts thermal earth noise

$\overline{G}_{D_i}$ = average gain with respect to discrete sources

A_R = effective antenna area

The complexity of the model illustrated in Figure 2.3.1 is necessary to account for all factors which affect the output signal and the output noise of the receiver.

Each source of interference is expressed in terms of its equivalent brightness temperature. There are three major sources of interference:

[1]Normalized percentage is a ratio or the fraction of the energy absorbed or lost where 1.0 represents total energy otherwise available.

(1) noise from the sky arrives at the antenna over the front half of the antenna when the antenna is pointed at a synchronous satellite; (2) noise from terrestrial sources, or indigenous noise, arrives at angles slightly above the horizontal; and (3) noise from the hot earth arrives over the back half of the antenna.

Beyond the atmosphere, cosmic noise originates as well as noise from discrete radio sources. This noise is attenuated in traveling to the antenna through the atmosphere and any rain or clouds which may be present. Noise also originates in the atmosphere and ionosphere due to black body radiation, and is equal to the product of the medium absorption factor and ambient temperature. The total brightness temperature at the front half of the antenna is

$$T_s = \left[T_c(1-\alpha)\ (1-\beta) + \beta T_{atm} + 2T_{ION}\right](1-Q_N) + Q_H T_r \qquad 2.3.1$$

where $T_c = T_{CK} + \sum_i T_{D_i}$. The last term in Equation 2.3.1 is due to absorption by rain and clouds.

At low angles above the horizontal the antenna is susceptible to energy traveling in a horizontal direction. The major portion of this energy is indigenous noise and interference from other systems. The indigenous noise can be attenuated by rain. A contribution to the brightness temperature in the horizontal direction is then made by the rain and is equal to the product of the ambient temperature of the rain and the percentage of the energy absorbed. Total brightness temperature in the horizontal direction is then

$$T_H = T_I(1-Q_H) + T_r Q_H \qquad 2.3.2$$

The back of the antenna is exposed to black body radiation from the ground and the brightness temperature over this region is approximately the ambient temperature of the ground since the ground is nearly a perfect absorbing medium.

$$T_B = T_E \qquad 2.3.3$$

With all potential sources of interference expressed in terms of an equivalent brightness temperature, the effective antenna temperature is given by the relation

$$T_A = \frac{1}{4\pi}\int_0^{\pi}\int_0^{\pi} T(\varphi,\theta)\ G(\varphi,\theta)\ \sin\theta\ d\theta d\varphi \qquad 2.3.4$$

where $T(\varphi,\theta)$ is the brightness temperature at a particular direction of arrival. Assuming the brightness temperature defined in Equations 2.3.1 - 2.3.3 to be constant over their solid angles of interest, Equation 2.3.4 can be rewritten as

$$T_A = \frac{1}{4\pi}\left\{\Omega_s T_s \bar{G}_S + \Omega_I T_I \bar{G}_I + \Omega_E T_E \bar{G}_E\right\} \qquad 2.3.5$$

where Ω_s, Ω_I and Ω_E are the solid angles over which the antenna looks at the sky, indigenous noise, and the earth, respectively and $\bar{G}_S$, $\bar{G}_I$ and $\bar{G}_E$ are the average antenna gains over these solid angles respectively.

The assumption of constant brightness temperature over each of the three solid angles is good for T_s and T_E (except for the contribution of discrete sources on T_s). And although the indigenous noise depends upon the direction of arrival, there are not sufficient data available to make a more rigorous treatment worthwhile.

Assuming $\psi = 10°$, values for the three solid angles are $\Omega_s = 2\pi - \Omega_I$, $\Omega_I = 2\pi\psi = .109$ and $\Omega_E = 2\pi$ steradians. The antenna noise power which is given by KBT_A is attenuated by the transmission line to the receiver terminals. The total system noise temperature referenced to the receiver input terminal is

$$T_N = T_A(1-L) + LT_{RF} + T_E \qquad 2.3.6$$

where T_E is the effective receiver temperature.

The desired signal experiences atmospheric, ionospheric, rain and feeder line absorption along with a possible antenna polarization mismatch loss due to Faraday rotation in the ionosphere. At the receiver input terminals the desired signal strength in watts is

$$S = \frac{P_T\ A_R(1-F_L)(1-\alpha)(1-\beta)(1-Q_N)(1-L)}{4\pi R^2} \qquad 2.3.7$$

where P_T is satellite ERP.

The output signal-to-noise ratio can be expressed in terms of the input signal strength and noise temperature by the relationship

$$(S/N)_o = I\frac{S}{KT_N B} \qquad 2.3.8$$

where I is the modulation improvement factor and B is the system noise bandwidth (predetection). The previous equations can then be combined to give the output signal-to-noise power ratio of the receiver.

$$\frac{S_o}{N_o} = \frac{P_T\ (1-F_L)(1-\alpha)(1-\beta)(1-Q_N)(1-L)A_R I}{4\pi R^2 KB\left\{T_A(1-L) + LT_{RF} + T_E\right\}} \qquad 2.3.9$$

where, T_A, the antenna temperature is

$$T_A = \frac{\overline{G}_s}{2}\left(T_{TK}(1-Q_N) + T_r Q_N\right) + \frac{\psi}{2}\,\overline{G}_I\left(T_I(1-Q_H) + T_r Q_H\right) +$$

$$\frac{T_g \overline{G}_E}{2} + \overline{D} + oT_{RF} \qquad 2.3.10$$

The contribution to antenna temperature from discrete radio sources, $\overline{D}$, is given by:

$$\overline{D} = \frac{1}{4\pi}\sum \Omega D_i T_{D_i} (1-\alpha)(1-\beta)(1-Q_N)\,\overline{G_{D_i}}$$

Finally the total background noise (cosmic noise temperature) is given by:

$$T_{TK} = T_{CK}\,(1-\alpha)(1-\beta) + \alpha T_{ION} + \beta T_{atm}$$

Equation 2.3.9 is the system equation and relates all paramemters which determine the system operation. It holds only for linear modulation improvement factors such as FM improvement. For other types of systems a simple modification is necessary.

2.4 ENRIVONMENTAL EFFECTS

The environmental effects which enter the system equation have been treated fairly extensively in the literature. They may be broadly categorized into two groups (1) environmental attenuation and loss factors, and (2) environmental noise. These effects are treated extensively in Appendices A and B respectively. In particular, consideration is given to values for cosmic noise brightness temperature (T_{TK}), atmosphereic attenuation (β), ionospheric absorption (α), values for rain attenuation at various frequencies, losses due to Faraday rotation, and the information presently available on indigenous noise.

In comparison to T_{TK}, T_{atm}, and β the effects of T_{ION} and α may be considered negligible. Also, loss due to Faraday rotation is insignificent above 2 Gc/s. For the other frequencies three polarization systems are considered, and each will yield a different loss due to polarization mismatch.

Type I - Both transmitting and receiving antennas are linearly polarized.

Type II - The transmitting antennas are circularly polarized and the receiving antenna is linearly polarized.

Type III - Both transmitting and receiving antennas are circularly polarized.

For Type I, the maximum loss versus frequency is given in Table A-2 of Appendix A.

A polarization system of Type II obviously results in a 3 db loss. Type III systems should be lossless except in the case of extreme polarization rotation when a change in the sense of circular polarization is experienced. For this condition the loss could be greater than 20 db.

At the present time, the available data on indigenous noise is limited and outdated. CRPL is currently establishing a program to obtain extensive indigenous noise data and develop meaningful noise statistics. The current standard noise data is found in the ITT Handbook. This data presents the noise in terms of equivalent field strength. Indigenous noise values are given up to 1.0 Gc/s for urban or city locations. Urban indigenous noise decreases exponentially with frequency.

On a log-log plot it is linear. By extending this line of the log-log noise versus frequency plot beyond 1 Gc/s values were extrapolated out to 12 Gc/s.

The data in terms of equivalent noise field strength (E_i) can be converted to an equivalent brightness temperature, through the relation

$$T_I = \frac{E_i^2}{z_o} \frac{\lambda^2}{4\pi K(\Psi/2)} \frac{K_n^2}{B} \qquad 2.4.1$$

where E_i is the noise field strength given by the ITT data for a 10 Kc bandwidth, λ is wavelength, z_o is the impedance of free space which is 120π ohms, K is Boltzman's constant, $\Psi/2$ is the ratio of the angle subtended by the indigenous noise at the antenna to the total solid angle, 4π, K_n is a correction factor to convert the basic field strength data to field strength for other than 10 Kc, and B is bandwidth. (See Appendix B)

2.5 ANTENNA PATTERN FACTORS ($\bar{G}_E$, $\bar{G}_S$, $\bar{G}_I$)

The antenna gain in the direction of interfering sources is the direct measure of the interference suppression characteristics of the antenna. The solid angles, Ω_E, Ω_I and Ω_S over which $\bar{G}_E$, $\bar{G}_I$ and $\bar{G}_S$ are determined, make up the total solid angle of 4π steradians, i.e., $\Omega_E + \Omega_I + \Omega_S = 4\pi$. Every point on the antenna pattern is then considered to fall within angles corresponding to average gains of $\bar{G}_E$, $\bar{G}_I$ or $\bar{G}_S$.

The average gain of the antenna over the total solid angle is the radiation efficiency N_R.

$$\bar{G} = \frac{1}{4\pi} \int_{4\pi} G \, d\Omega = N_R \qquad 2.5.1$$

By integrating separately over the individual solid angles of interest, we have

$$\frac{1}{4\pi} \int_{\Omega_S} G d\Omega + \frac{1}{4\pi} \int_{\Omega_I} G d\Omega + \frac{1}{4\pi} \int_{\Omega_E} G d\Omega = N_R \qquad 2.5.2$$

which becomes

$$\frac{\Omega_S}{4\pi} \bar{G}_S + \frac{\Omega_I}{4\pi} \bar{G}_I + \frac{\Omega_E}{4\pi} \bar{G}_E = N_R \qquad 2.5.3$$

Each term in the equation represents the normalized percentage of radiated or received power in the sectors defined by solid angles Ω_S, Ω_I and Ω_E with the total normalized power defined as the radiation efficiency. As the main lobe antenna gain is increased, a greater percentage of the power is radiated through the main lobe and less power is radiated through the sidelobes and backlobes which determine $\bar{G}_I$ and $\bar{G}_E$. As the mainlobe gain increases, $\bar{G}_S$ will increase and $\bar{G}_I$ and $\bar{G}_E$ will decrease.

The average gain factors can be determined, as a function of mainlobe gain, from the patterns of the antenna. For an isotropic antenna having radiation efficiency of 1, the average gain factors $\overline{G}_S$, $\overline{G}_I$ and $\overline{G}_E$ are each equal to 1. The relative effect of the antenna on the amount of energy radiated or received in the sectors Ω_S, Ω_I and Ω_G in this case is proportional to the value of their respective solid angles. An antenna constructed to have gain in the mainlobe modifies the effective energy received from different directions causing the average gain to increase in the direction of the mainlobe and to decrease in the direction of the sidelobes and backlobes. The average gain of any antenna neglecting radiation loss is 1. Only the distribution of gain varies with angle as antennas are made directional. For the case of determining the relative effect of antenna directivity on interference suppression, it is necessary to separately determine the average gain of an antenna over each sector for which the interference effects are different. It has been determined for purposes of analyzing the effect of interference on reception from satellites that interference may be considered to arrive from these separate types of sources identified generally as the sky, the man made environment on earth, and the earth itself. The solid angles on which each of these distinct types of sources effect reception have been identified as Ω_S, Ω_I, and Ω_E respectively. Ω_S is the solid angle above earth limited by an angle above the horizon of 10°. Ω_I is the solid angle from the horizon to 10°, and Ω_E is the hemisphere including the earth below the horizon. Ω_S includes in effect noise from the sky. Ω_I includes man made indigenous noise. Ω_E includes noise radiated from the earth itself.

To determine the effect of noise of the three types just described, it may be assumed that each is homogeneous within its solid angle. Thus, the related effect of an antenna on reception or suppression of noise relative to reception of a signal must be determined by calculating the average gain of the antenna in the directions bounded by the solid angles Ω_S, Ω_I and Ω_E. For such a calculation the look angle of the antenna must be taken into account and average gain must be calculated from the antenna pattern oriented in space such that the mainlobe is in the direction of the look angle--that is in the direction of the satellite. For the case of this study a look angle of 43° (θ_s = 47°) is assumed as a reasonable angle for a station in the United States receiving from a synchronous stationary satellite.

Figure 2.5.1 shows the results of calculating average gain factors $\bar{G}_S$, $\bar{G}_I$ and $\bar{G}_E$ for an antenna look angle of 43° and antennas having varying values of mainlobe gain. It was assumed for these calculations that yagis will be used for gains up to about 15db mainlobe gain, whereas parabolas will be used for mainlobe gains of greater than 15db.

The principal difference between yagis and parabolas is the fact that a yagi has a relatively poor back to front gain ratio. Also, for increasing gain from something in the order of 3db to 15db there is very little decrease in the total energy received through the backlobe. The principal effect is a redistribution of energy received through the mainlobe and the sidelobes close to the mainlobe. Since this redistribution occurs within the solid angle Ω_S, there is no net effect on the average gain factors $\bar{G}_S$, $\bar{G}_I$ and $\bar{G}_E$.

In the case of the parabola--used for calculating results for mainlobe gains of greater than 15 db--the back to front ratio is much better than for yagis. Gain in the mainlobe is achieved by decreasing both backlobes and sidelobes including those sidelobes which for a look angle of 43° fall in the solid angle Ω_I. As gain is increased, a point is reached at which the effect of reducing backlobes and minor sidelobes has small effect on the energy in the mainlobe or major sidelobes close to the mainlobe. At this point the curves (for very high mainlobe gain) flatten out. The principal effect of increasing gain at high gains is a redistribution of energy from principal sidelobes, which already fall within the angle Ω_S, to the mainlobe also in this same solid angle. This has no effect on average gain factors $\overline{G}_S$, $\overline{G}_I$ and $\overline{G}_E$ because the net effect is little or no change in total energy received through the solid angles of concern, Ω_S, Ω_I, and Ω_E.

The results shown in Figure 2.5.1 indicate the significance of using directional antennas with particular emphasis upon reduction of effective gain in the direction of earth noise (backlobe) and indigenous noise. For high angle reception improved performance in rejection of earth noise and indigenous noise can be realized from antennas having low back to front ratio and low order minor sidelobes. $\overline{G}_S$ and $\overline{G}_E$ will not vary significantly with antenna look angle. $\overline{G}_I$, on the other hand, can be significantly less for look angles greater than 80°. This is because antenna sidelobes at $\pm$ 90° from the mainlobe can be reduced easily, whereas, the other sidelobes cannot be so easily reduced for

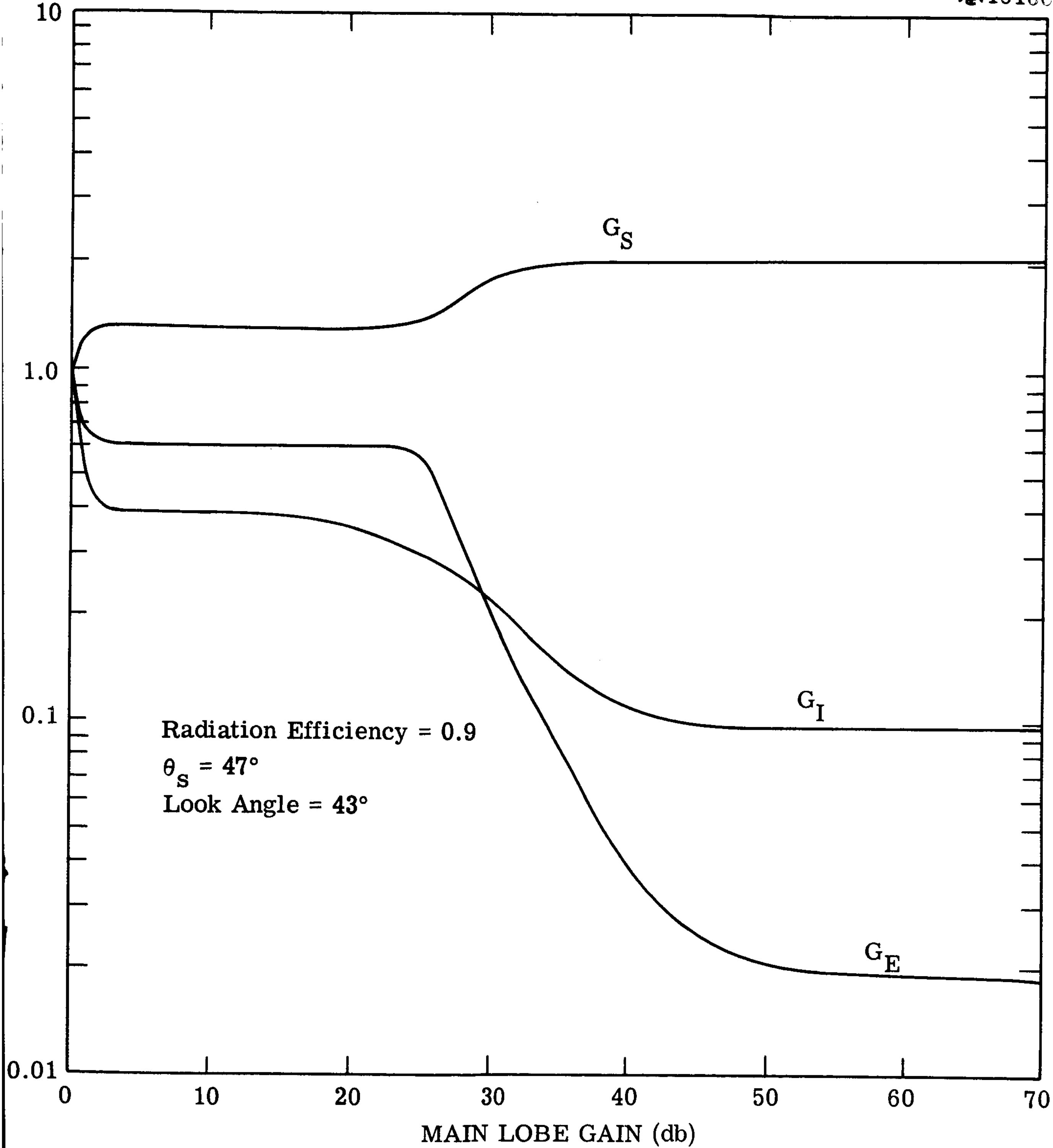

Figure 2.5.1. Average Antenna Gain Factors Versus Main Lobe Gain.

3.0 COST VERSUS RECEIVING SYSTEM PARAMETERS

3.1 GENERAL

In evaluating the receiving system's cost relative to required satellite power and frequency of operation, costs relating to four distinct parameters of the receiving system have been studied separately--Cost versus Noise Figure (F), Cost versus Modulation Improvement (I), Cost versus Antenna Size (Gain) and Cost versus Feeder Loss (L). In some cases it is difficult to relate a cost component to one of these parameters independent of the values of the other parameters. An example of this is the problem of relating cost to improvement factor independent of noise figure.

Besides the four primary receiver cost factors referred to above, other factors, which can be considered as secondary cost factors, are also evaluated. These include the cost of reduction in antenna average side lobe and back lobe level as well as the cost of mounting the RF amplifier and mixer at the antenna terminals.

3.2 METHODS USED IN COST ANALYSIS

3.2.1 General

In determining the cost of the receiver components, the major sources of information were manufacturers of components which could be used in a satellite television system, and various research and development organizations working in related fields. In this way, first-hand information has been obtained on the present and expected future state-of-the art in design techniques and the cost of components involved in implementing such techniques. This basic input information was supplemented, where possible, through reference to equipment catalogs and other literature.

3.2.2 Manufacturers and Research Groups

To accurately predict the cost of a satellite TV receiving system that might be used by 1970, it is necessary to predict what devices will be available by then, what effect these devices will have upon improvement in reception, and the nature of the market demand that will exist for these devices. Many of the components which are used today will still be used in 1970; but changes in market demand, improvements in materials, and improvements in production processes can be expected to improve the characteristics and reduce the cost of these components.

By consulting a number of research and development groups, fundamental technical information has been obtained regarding expected new component development, the characteristics of present components, and information regarding the effect of environmental parameters on propagation and reception. By consulting electronics manufacturers, fundamental information has been obtained on the cost of produced components and the effect of market demand on cost. Manufacturers of large quantities of components were consulted to ascertain the effect of large-scale production on the cost of a component, and to ascertain what it would take in the way of demand to realize large-scale production or low-cost production of components which are not currently mass produced. An examination has been made of the trend in demand and cost of those items that show promise in the reception of television from satellites.

The manufacturers and research groups who were asked for advice were, on the whole, very willing to participate in the program and were extremely helpful. A great deal of interest was shown in the subject under study. Without the cooperation of such groups, a meaningful report on costs could not have been assembled. The groups consulted directly for comment and discussion are listed below:

Andrew Corporation
Oak Manufacturing
Zenith Radio Corporation
Standard Kohlsman
University of Illinois EE Department
The General Electric Corporation
Radio Corporation of America
Texas Instruments
Hughes Aircraft
Arthur D. Little Company
Channelmaster Corporation
Technical Appliance Corporation
Wheeler Laboratories
Dorne and Margolian
Airborne Instruments Laboratory
International Telephone and Telegraph
Microwave Associated
Sage Laboratories
Sylvania
Raytheon
Lincoln Laboratories
Massachusetts Institute of Technology, EE Department

If time had permitted, other groups would have been contacted. In this report, specific data points are not related to their sources. Most points are obtained from a combination of sources.

3.2.3 Literature and Catalogs

For some components, information regarding cost was obtained from equipment catalogs. The information regarding feeder cost falls into this category. Due to the fact that the major cost of feeder lines is the cost of material, and the basic structure is not expected to change, significant cost changes are not expected to occur due to increased market demand.

Literature surveys and analyses were made to determine the advantages of possible modulation techniques in terms of improvement and the effects of various environmental factors.

3.2.4 Methods of Extending Cost Information

Cost information from the various manufacturers was usually based on some anticipated market demand. Due to the variation in existing market demand from component to component, the quantity upon which the cost estimates were based varied widely from 1 to 10^6. For our purposes, it is necessary to determine the cost in quantities up to 10^6. In some cases this means a lengthy cost projection.

The basic method for cost projection which has been used is the application of learning curves or improvement curves. This method was first applied to the aircraft industry in World War II and is currently widely accepted as a cost projection basis by the microwave industry.

Learning curves are based upon a very simple principle. This principle assumes that if the cost to produce the n th item is X dollars, the cost to produce the 2n th item will be KX dollars where $0 \leq K \leq 1$, and K is determined by the particular production process. For instance, some manufacturers of microwave equipment use K = .85. The learning curve process is illustrated in Figure 3.2.1 where the cost to produce the first item is \$1000 and K = .85. The cost to produce Item 2 is \$850 or .85 (\$1000). The cost to produce Item 4 is then (.85) (\$850) or \$722 and so on.

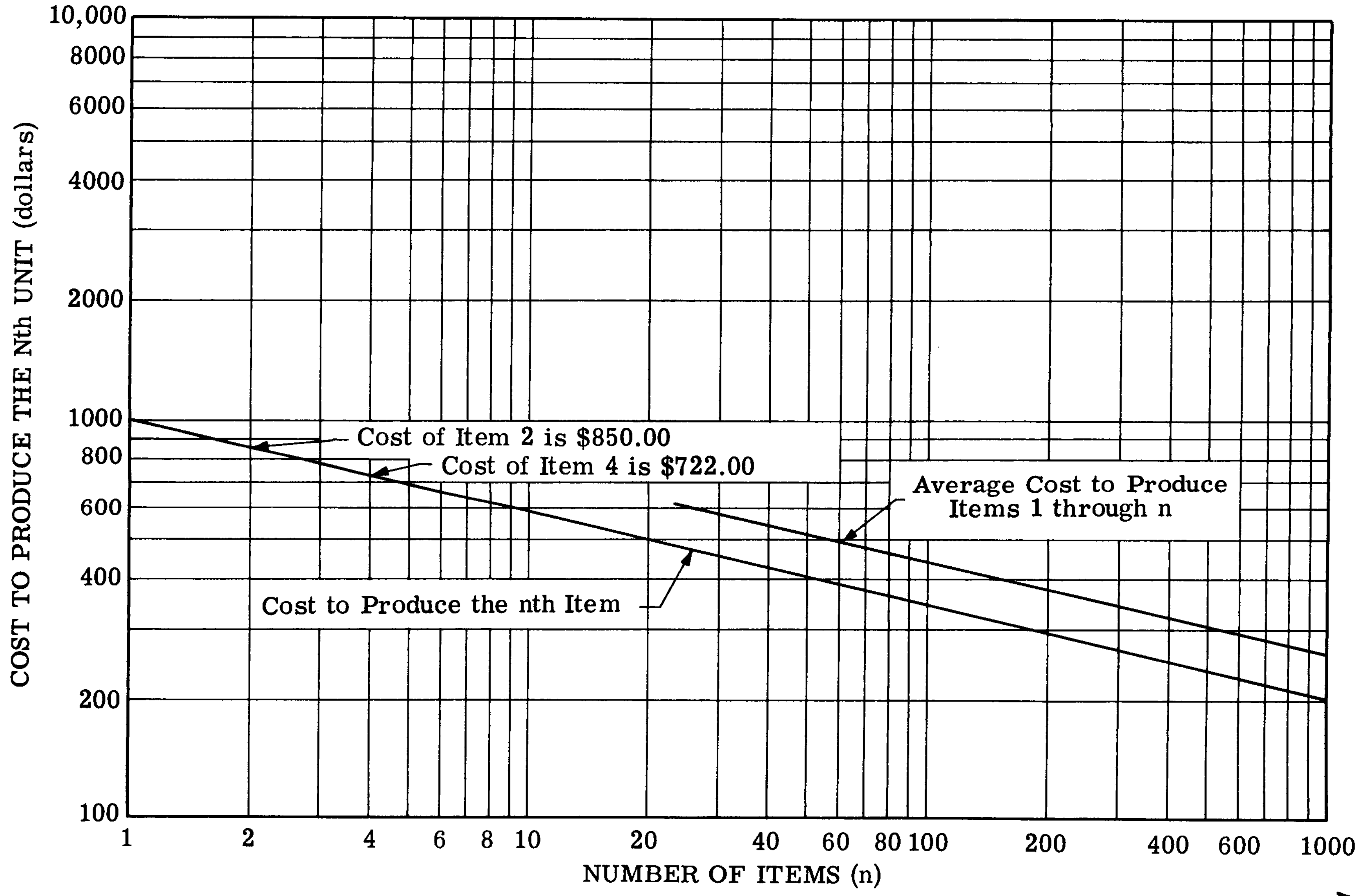

Figure 3.2.1. Learning Curve for K = 0.85.

If the market is such that we can anticipate selling Y units, each unit can be sold at the average production cost of the Y units which is just the area under the improvement curve from one to n divided by n. This average value is readily available in tables and will be used as the price for a certain component with market demand for n units. It can be shown from the principle of the learning curve that the average price curve for quantity n is parallel to the unit cost curve, but above it. If either the average cost curve or the unit cost curve is known, the other can be easily determined.

The learning curve technique has been used in this study. K for a specific component has been determined by obtaining the cost of an item for two specific quantities n_1 and n_2 and drawing a straight line plot on log-log plot as was done in Figure 3.2.1. This establishes the value of K and serves as a basis for further cost projections.

It should be pointed out that the use of learning curves in cost projections has limitations. If the production process can be assumed to change drastically for high quantity demands, then the learning curve must be adjusted at this production break. Nevertheless, it is still a helpful tool in cost projections.

3.2.5 New Techniques and Components

In the investigation of components to be used in a satellite TV receiving system several uncertainties were uncovered. These are mainly in regard to the performance characteristics of these components. This makes an accurate cost analysis of these areas very difficult although this type of problem can be anticipated in any projection of the state of the art. In handling these uncertainties and placing values on them, the rate of development of the state of the art is considered and applied to project these values. Where this cannot be done, the range of uncertainty is noted and a fairly "safe" characteristic is used.

Examples of components whose characteristic definition is uncertain for the period 1970 are given below:

Transistors - the upper frequency limit and possible noise figure at this frequency limit

Schottkey Barrier Diodes - the noise figure of a receiver using this diode as a first stage and the diode's stability

Gunn Effect Oscillators - whether or not these oscillators can be produced to oscillate at a predetermined frequency.

The above are three devices which can, depending on their characteristics, alter the price picture considerably.

3.3 COST VERSUS RECEIVER NOISE FIGURE (F)

3.3.1 General

The following discussion of receiver noise figure and its associated cost is considered for three frequency ranges -- VHF, UHF, and microwave frequencies, respectively. The reason for this separation is that the type of available hardware changes in going from one of these frequency ranges to the next and the demand for components change. It is felt that the ranges of desired noise figure can be developed on a common basis over each of these frequency ranges. Due to the difference in current demand for the components in each range, the method of cost projection will be different.

The noise figures discussed in the following sections will be for the receiver only and will not include contributions from transmission line losses. Receiver noise figure and transmission line loss are combined in the system equation to give the overall noise figure.

3.3.2 Cost Versus Receiver Noise Figure at VHF (100 Mc/s to 300 Mc/s)

A practical limitation on the improvement that is obtainable by reducing the noise figures of VHF receivers is the high cosmic noise temperature and large value of indigenous noise that exist in the VHF frequency range. As a result of these effects, extremely low noise receivers will not lower the overall system noise to any significant extent. Improvements beyond a noise temperature of 2 db (effective temperature of 170°) will go practically unnoticed.

As a cost base for the VHF band, present VHF-TV tuners may be used. A typical block diagram for such tuners is shown in Figure 3.3.1. The input signal goes through a preselector and amplifier, and then is mixed down to the IF frequency. At these frequencies, it is easy to obtain high amplification with the amplifier. The contribution to noise figure from the mixer is therefore neglibile as can be seen from the chain equation for noise figure.

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

where

G_n = gain of n th stage as a ratio

$$F_i = \frac{\frac{S}{N}\text{ power ratio at input of n th stage}}{\frac{S}{N}\text{ power ratio at output of n th stage}}$$

The noise figure F can also be expressed as:

$$F = \frac{\frac{S_i}{N_i}\text{ power ratio at input to receiver}}{\frac{S_o}{N_o}\text{ power ratio at output of receiver}}$$

where

$Ni = K\ B\ T_o$

K = Boltsman's Constant = 1.38×10^{-23}

B = Bandwidth of receiver

T_o = 290°K

Noise figure expressed in db is 10 log F. Considering the amplifier and preselector as making up the first stage the gain is 25 db, or about 300. The second term is then negligible.

The overall noise figure of a present VHF tuner is from 5.5 to 7.0 db, the range being associated with production and assembly variations. The amplifier has a noise figure of about 2 db to 3 db. Loss in the preselector accounts for the higher overall noise figure. When the receiver is switched to UHF operation, the VHF tuner is utilized as the first IF section of the receiver. When this occurs, the VHF tuner is switched to channel 1 which is at 45 Mc/s. The noise figure of the VHF tuner is optimized at channel 1 for this operation and has a typical value of 2.6 db. This illustrates the noise figure which

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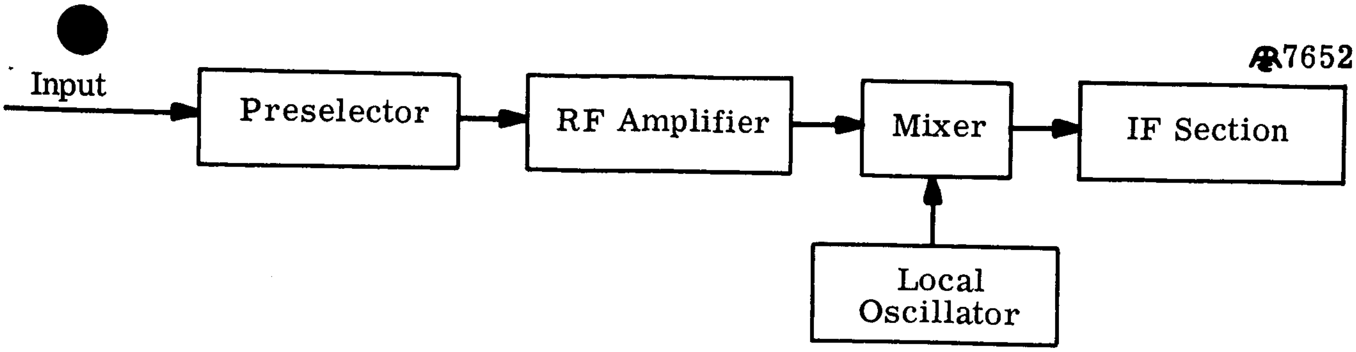
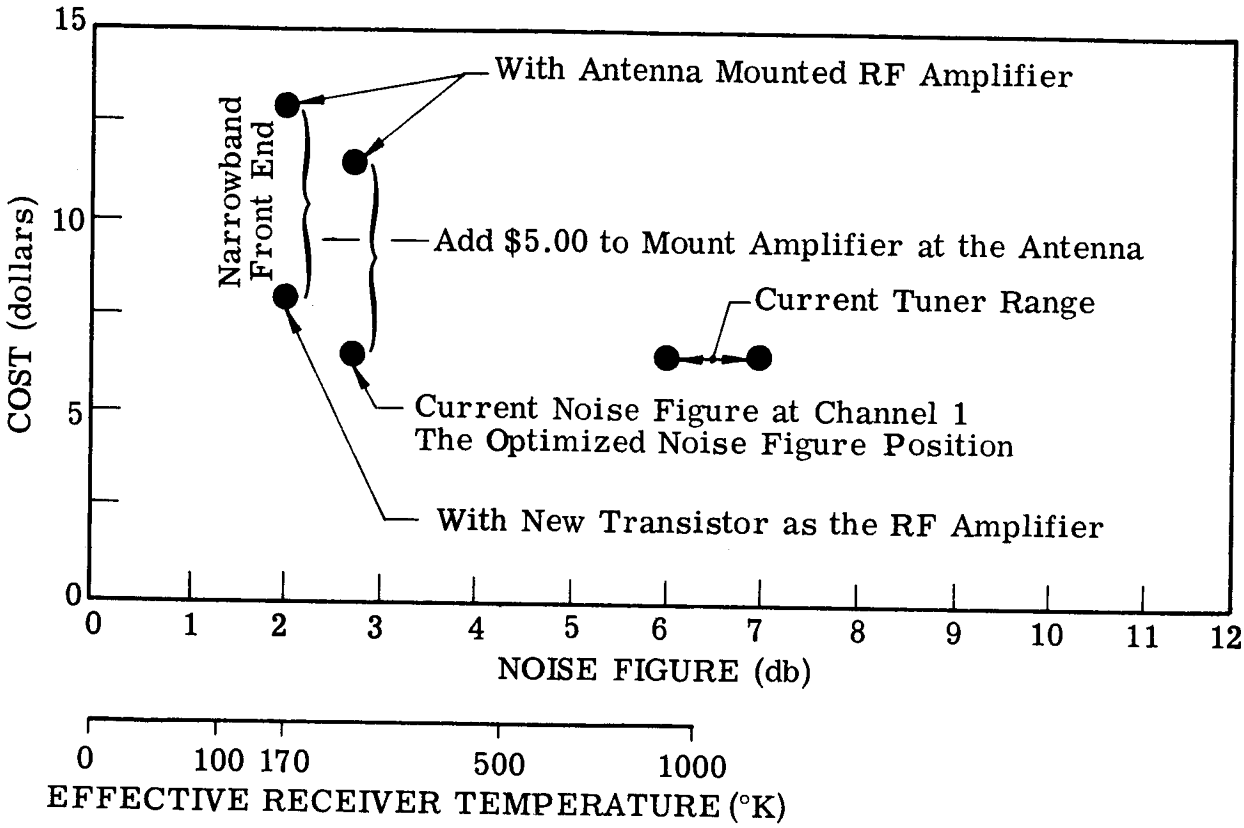
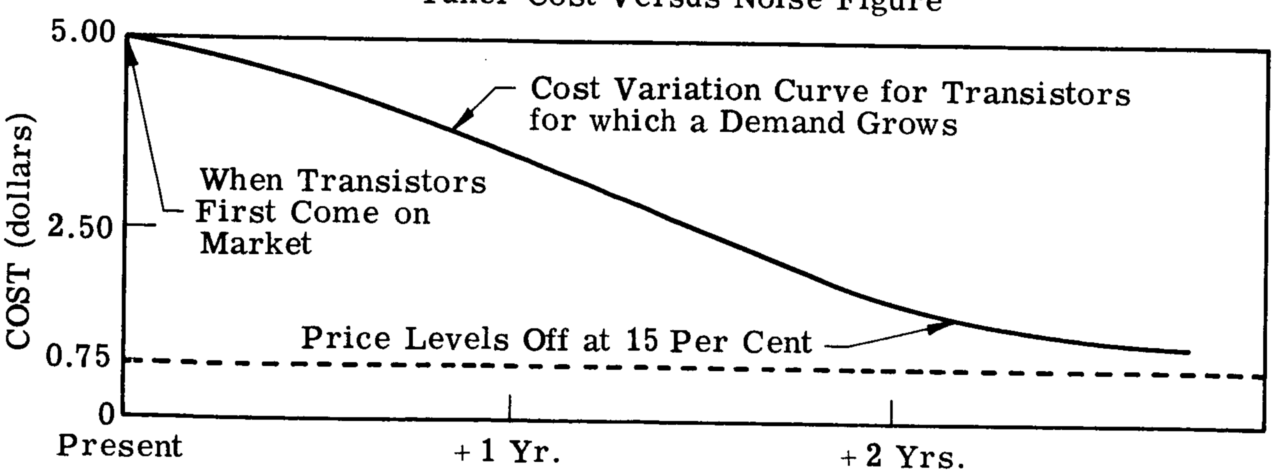


VHF Tuner Configuration



Tuner Cost Versus Noise Figure



TRANSISTOR PRICE VARIATION WITH TIME

VHF Tuner Versus Cost

Figure 3.3.1. Cost Versus Noise Figure, VHF, Based on a Million Demand.

can be achieved if the present tuner is optimized for noise figure at a particular frequency. This then gives another point on the VHF noise figure curves as shown in Figure 3.3.1.

A receiver for satellite television could have two basic configurations. The first is a VHF tuner which could be used for satellite or ground transmissions with the noise figure optimized at the satellite frequency, or it could have a separate tuner which is optimized for satellite usage. The cost of either tuner would be about \$6.00, which is the current VHF tuner cost to the assembler. In the latter case the total tuner cost would be about \$14.00.

Another point on the VHF curve may be developed by using an available low noise device which is currently high priced, but by 1970 will be moderately priced. This device is a transistor which currently sells for \$5.00. It is expected that after a two-year period this device will sell for \$0.75 if a reasonable demand occurs. This projection is based on the type of cost variation with time that previously developed transistors have experienced. The main characteristic of the transistor cost variation curve is that if a transistor costs X dollars when it first comes on the market, it can be expected to level off at a price of \$0.15X after a two-year period. This is illustrated in Figure 3.3.1 for this particular transistor. With the cost of \$0.75 by 1970, the addition of this transistor to the current type of VHF tuner would cost an additional dollar. This transistor has a noise figure of 1.0 db. In an optimized tuner, this noise figure can be realized to within 1.0 db--based on previous design experience--

giving an overall noise figure of 2.0 db. Due to the availability of VHF tuners of acceptable quality, the cost of the tuners should vary little with the quantity used in the satellite television system since it will not appreciably affect the market.

A possible configuration is to mount the amplifier at the antenna in order to reduce the contribution of line loss to the overall receiver noise figure. The added cost of doing this is $5.00. This includes the weather-proof casing for the antenna, a choke coil for picking off the D.C. power from the down line to operate the amplifier and the power supply. This configuration is only practical if a transistor amplifier is used.

The cost of VHF tuners has been developed on the basis of a large quantity demand. The modifications to the present tuner which will improve the noise figure are not major modifications and should not affect the VHF tuner market significantly. The cost of the tuners should not change with quantity.

3.3.3 Cost Versus Receiver Noise Figure at UHF (300 Mc/s $\leq$ f $\leq$ 1.0 Gc/s)

Due to the relatively small values of environmental noise at the UHF frequencies, low noise devices may be advantageous. For this reason cost versus noise figure will be developed over a wide range of noice figure (F), beginning with the currently available UHF tuners.

The present UHF tuner is considered a basis for obtaining cost versus noise figure for large-quantity production tuners. Modifications to the tuner and changes in the production technique which would reduce the noise figure are considered. Based on production experience and cost of necessary materials, an attempt is made to associate cost with these improvements. In this manner, a cost versus noise figure (F) relation is defined over a range of F.

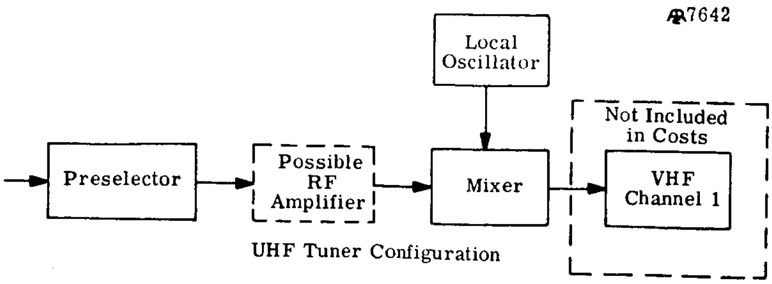
The current UHF tuner configuration, which is used by all major tuner manufacturers, is shown in Figure 3.3.2[1]. Figure 3.3.2 also shows the tuner manufacturer's selling price which is the receiver manufacturer's cost for the UHF portion of the tuner, for specific modifications to the present UHF tuner arrangement, and the resulting noise figure for the UHF branch of the tuner. These costs do not include the VHF (Channel 1) equipment shown in the block diagram.

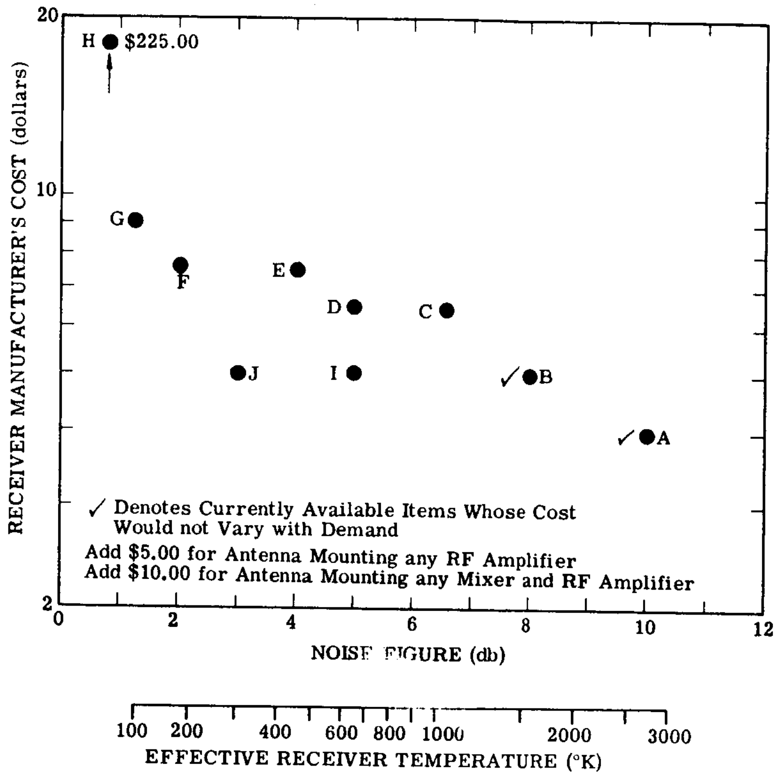
The noise figure estimates from the various manufacturers varied by ±0.5 db from the value of 10 db for present tuners shown in Figure 3.3.2. For the other configurations the value of F is a typical value.

In some cases the optimum noise figure (F) can be lower. The indicated F is for the particular frequency range for which the tuner is optimized.

As shown, present UHF tuners have an F of 10 db at the frequency for which they are optimized. Although the 10 db figure occurs at the low end of the UHF region and rises to 12-13 db at the higher end of the band, it could be designed to occur at any frequency

[1] When the tuner is in UHF operation, the output of the UHF branch is fed into the input of the VHF section, which in turn acts as a first IF. Currently, the UHF sections cost about $4.00 and have noise figures of 9-10 db, while the VHF tuner costs $6.00 and has a noise figure of 5-6 db. The proposed modifications will be to the UHF sections.





A - Present Tuner (No RF Amplifier)

B - Present Tuner, Better Selection of Component (No RF Amplifier)

C - Present Tuner, Better Selection of Component Plus RF Amplifier Unlimited Dynamic Range

D - Present Tuner, Better Selection of Component Plus RF Amplifier Limited Dunamic Range

E - Present Tuner, Better Selection of Component Plus New Transistor RF Amplifier Stage, Wideband

F - Present Tuner, Better Selection of Component Plus New Transistor RF Amplifier Stage, Narrowband

G - Present Tuner, Better Selection of Component Plus New Transistor RF Amplifier Stage, Narrowband Designed Specifically to Optimize Noise Figure

H - Present Tuner, Better Selection of Component Plus Uncooled Parametric Amplifier

I - Present Tuner, Better Selection of Component Except that Schottkey Barrier Diode is Used as Mixer Wideband (No RF Amplifier)

J - Present Tuner, Better Selection of Component Except that Schottkey Barrier Diode is Used as Mixer Narrowband (No RF Amplifier)

Figure 3.3.2. Cost Versus Noise Figure, UHF, Based on a Million Quantity.

up to 1.5 Gc/s without increase in cost. To reduce F, several alternatives are available. Among these are the following:

1. Better selection of components in the production process
2. Use of a Schottkey Barrier Diode as a mixer
3. Use of a transistor amplifier before the mixer
4. Use of a parametric amplifier before the mixer.

Through better selection of components, an improvement of 2 db in F can be achieved. Since the cost of components is small, the increase in cost to achieve this is only $1.00. The second step in the noise figure improvement process is the incorporation of an RF amplifier using a currently available transistor. The noise figure of an amplifier depends on the dynamic range of the receiver. If the tuner is used solely for satellite television, a wide dynamic range would not be required. This is due to the stability of the radiated signal. A noise figure of 5 db is possible with a limited dynamic range receiver. For a wide dynamic range receiver which would be the case for a tuner serving the dual purpose of satellite television and ground television a 6.5 db receiver is possible. The increased cost of an RF amplifier would be about $2.50.

Improvement can be attained without an RF amplifier if a Schottkey Barrier Diode is used as the mixer. For noise figure purposes, this diode can be considered a perfect diode, such that the noise figure from the diode through the IF strip is the noise figure of the IF alone. Assuming that by 1970 the noise figure of Channel 1 (the UHF IF strip) will be 2.0 db the noise figure of the receiver will be 5.0 db for a wideband receiver and 3.0 db for a narrowband receiver. This is due to the fact that the preselector adds 3 db to the noise figure for the wideband case but only 1.0 db for the narrowband case.

Using a transistor with a 1.0 db noise figure, as was used in the VHF tuner costing, with the RF amplifier, further improvement can be achieved. Due to the high cost of this particular transistor, it would increase the tuner cost by $1.00 over the amplifier using the currently available transistor. The achievable noise figure would be 2.0 db for the narrowband case and 4.0 db for the wideband case. If this tuner were optimized for noise figure alone, the overall tuner noise figure would be within 0.2 db of the transistor itself giving a noise figure of 1.2 db with an additional $2.00 cost.

For further reducing the noise figure, a parametric amplifier must be used. An uncooled paramp at 1 Gc/s can achieve a noise figure of 0.81 db. Costing information for this particular paramp is available to quantities of 10,000. Extending this cost using a 85 per cent learning curve to a quantity of one million yields a per-unit price of $225.00.

The effective temperature for a noise figure of 0.81 db is 60°K and further improvement can only be achieved at far greater expense.

3.3.4 Cost of Microwave Tuners (1 Gc/s - 12 Gc/s)

Due to the different existing quantity demand for microwave components than the quantity demand for UHF-VHF tuners, a different cost basis will be established. Considering the many different types of components which are used at the microwave frequencies, and the numbers of these various components which are sold, they can be compared on a cost basis most accurately for very small quantity demands. Some components have been accurately priced for large quantities, but others have not. All microwave components, however, have established prices for small quantity production.

The cost versus noise figure curve will be developed for a quantity of one. Cost projections will be made using an 85 per cent learning curve. In many cases, the cost information was obtained for quantities greater than one. This cost information was then projected back from that quantity to a quantity of one on the 85% learning curve.

Most microwave manufacturers agree on the 85 per cent learning curve as a basis for cost projection. This was verified in costs for a particular item for different quantities. When plotted on the log-log plot the points determined, for most cases, an 85 per cent learning curve.

The basic configuration for the microwave receiver is the same as that for the UHF tuner--a preselector, possible RF amplifier, mixer first IF amplifier and local oscillator. In some cases for very low noise devices, a second low noise amplifier will be required so that the low noise figure of the first amplifier may be fully realized. These are the components which are costed for the receiver noise figure.

The various components which are used to generate the cost versus noise figure curve, will be discussed in sequence, starting with those components which yield a high noise figure and progressing in the direction of reduced noise figure. Frequent reference will be made to Figures 3.3.3 and 3.3.4 which show the cost of tuners (expressed in terms of these noise figures) versus cost and the types of receivers which are used to give a particular noise figure at different frequencies.

Local Oscillator and First IF Amplifier

A necessary item in any superheterodyne receiver is the local oscillator, and at microwave frequencies, they are expensive. Present local oscillator design techniques include a transistor oscillator at the VHF range followed by a varactor chain or step recovery diode. The highly non-linear action of the diode produces harmonics of the oscillator fundamental and one of these is used as the local oscillator signal. Step recovery diodes, or snap diodes, appear to be more efficient harmonic generators than varactor diodes. The above technique is usually used when crystal control of the local oscillator is desired.

A second method is to build the oscillator to operate at a high enough frequency such that the fundamental of the oscillator or one of its harmonics can be used directly as the local oscillator signal. However, a local oscillator of this nature, with the oscillator power which can be achieved from transistors, cannot be crystal controlled.

By 1970, due to anticipated improvement in solid state devices, local oscillator design should change significantly. This is due mainly to the increased RF power output of solid state devices

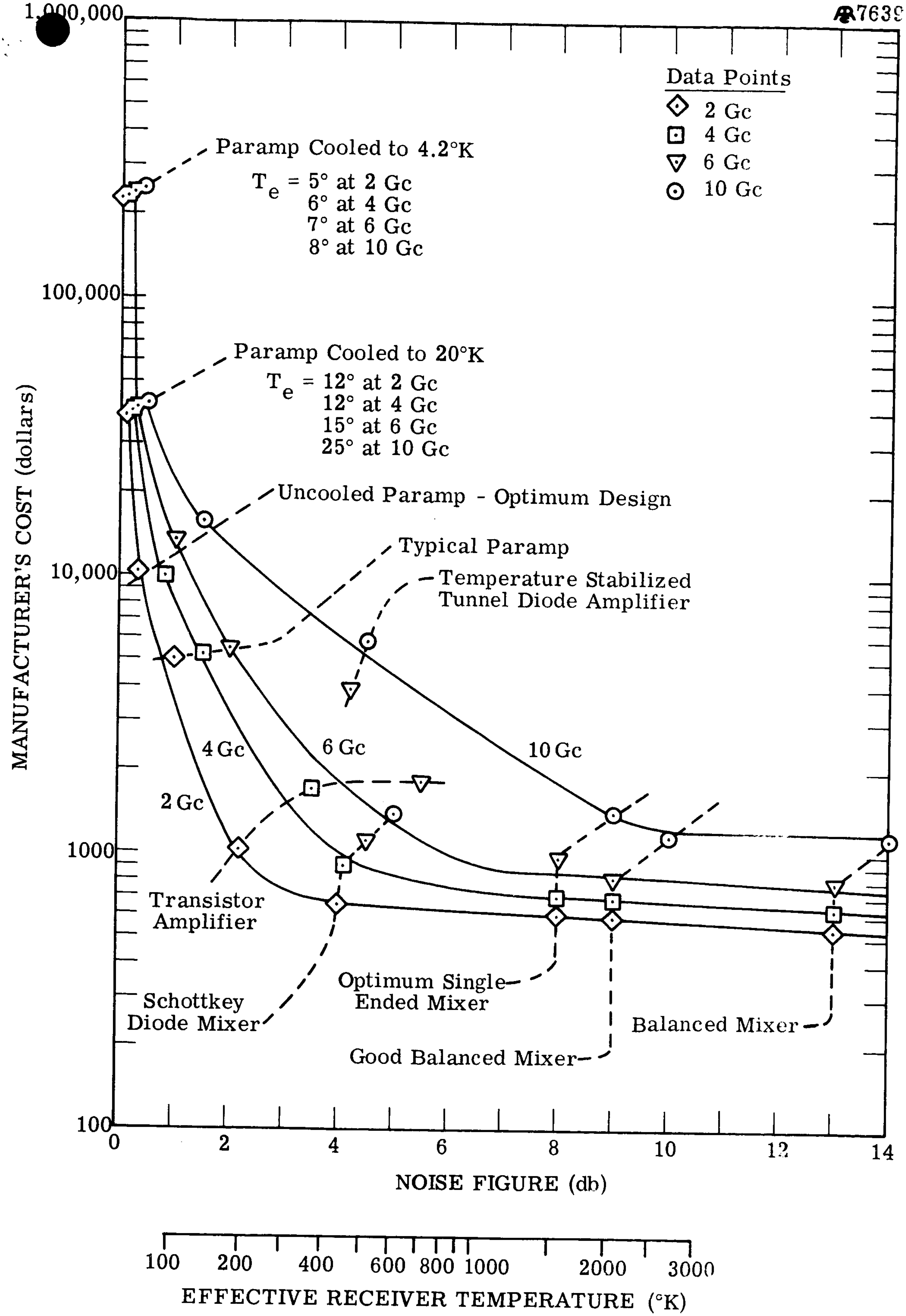


Figure 3.3.3. Cost Versus Noise Figure, Microwave, Quantity of One.

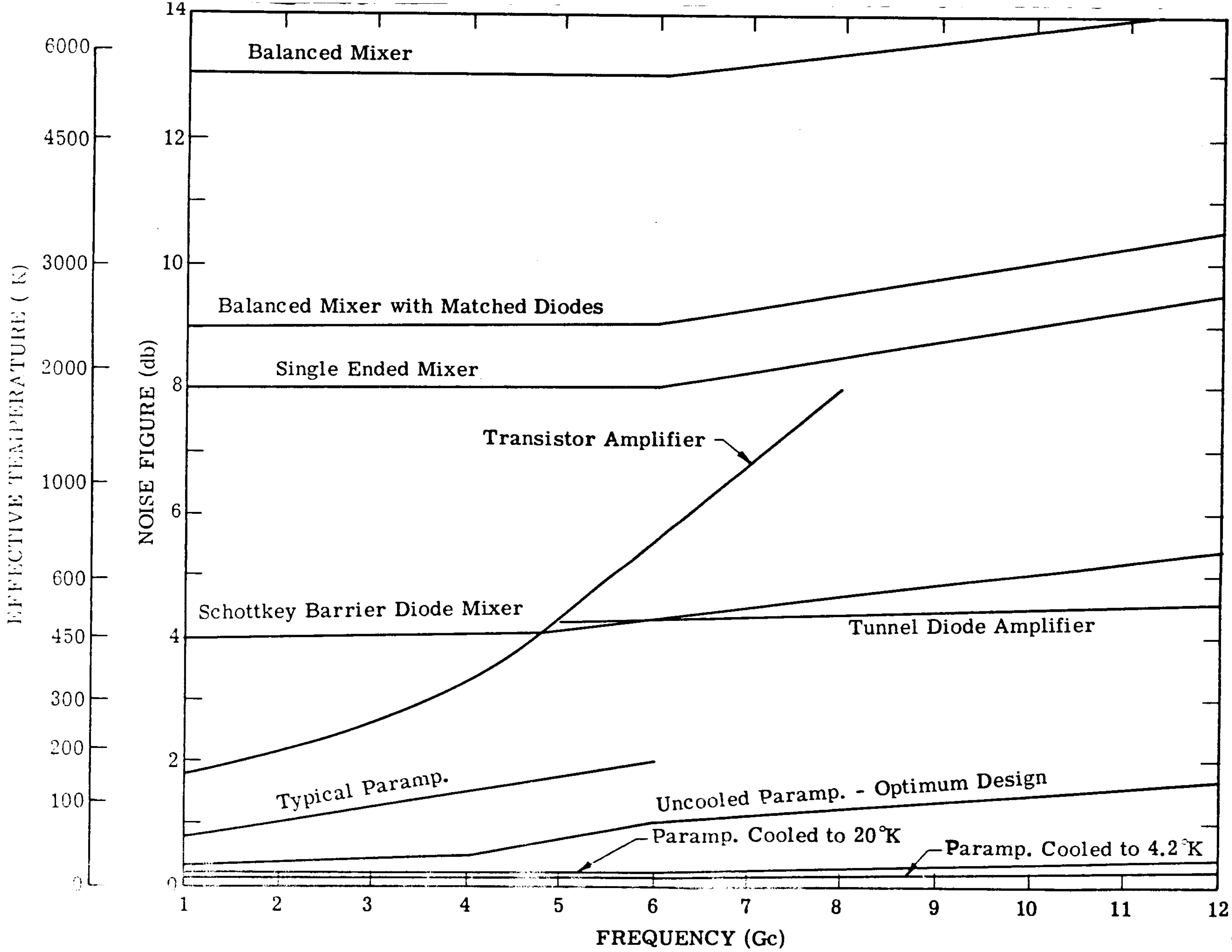


Figure 3.3.4. Noise Figure of Various Receivers as a Function of Frequency.

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at the microwave frequencies. One to ten milliwatts of local oscillator power are required to satisfactorily drive a diode mixer. By 1970, this power should be available from a single stage oscillator, either in the form of a signal at its fundamental frequency or a harmonic. However, only at the low end of the microwave range could an oscillator of this type be crystal controlled. Improvements in Silicon transistors should also reduce the number of varactor elements required for crystal controlled oscillators.

For silicon transistor local oscillators, the cost at 1970 for one is given below along with the cost of the first IF amplifier which is a transistor amplifier.

Frequency (Gc/s)	Local Oscillator Cost(dollars)	First IF Amplifier Cost(dollars)
2	300.00	200.00
4	400.00	200.00
6	500.00	200.00
8	700.00	200.00
10	900.00	200.00
12	1100.00	200.00

Balanced Mixers

A balanced mixer has two diodes which are driven by the same local oscillator. They have the advantage that the signal port and the local oscillator port are isolated. No signal is lost through the local oscillator line. A second advantage provided by the balanced mixer is that input noise components beating against other input noise components to enter the IF channel are cancelled out due to the phase opposition of the circulator.

The basic mixer structure is \$40.00, the diodes cost between \$10.00 a pair and \$50.00 a pair depending on whether or not their characteristics are accurately matched. For unmatched diodes a noise figure of 13 to 14 db is obtained. For the matched case a noise figure of 9-10 db is obtained. The cost of the balanced mixer with the local oscillator and first IF amplifier is shown in Figure 3.3.3. Figure 3.3.4 shows the noise figures which can be obtained at the different microwave frequencies.

Presently Available Single Ended Mixer

Single ended mixers have a single diode as the non-linear element. The major disadvantage is that attenuation must be provided at the local oscillator to isolate that port from the signal port. This attenuation reduces the local oscillator power at the mixer. This requires more basic local oscillator power. Costwise the single ended mixer is comparable to the balanced mixer. The increased local oscillator requirement leads to an increase in the cost of the overall configuration.

Schottkey Diode Mixer

The Schottkey diode which was discussed in Section 3.3.2 can be used at the microwave frequencies. An improved noise figure is available due to its low value of insertion loss. This mixer as well as the others discussed can be used up to 12 Gc/s.

Requirements for local oscillator power should be the same as for the present single ended mixer. The mixer receivers which have been discussed do not have an amplifier before the mixer.

Transistor Amplifier

The addition of a transistor amplifier to a well designed balanced mixer stage will reduce the noise figure further. The noise figure for transistor amplifier receivers shown in Figure 3.3.3, is based on realizing the noise figure of transistors, which will be available by 1969, to within .5 db. The upper frequency limit at which transistor amplifiers can be advantageously used is 6-7 Gc/s.

The cost of the amplifier at different frequencies is:

Frequency (Gc/s)	Cost of Transistor Amplifier(dollars)
2	300
4	1,000
6	1,000

This cost plus the local oscillator cost and a $100.00 mixer gives the total receiver cost.

Tunnel Diode Amplifier

Due to the anticipated availability of transistor amplifiers at the lower microwave frequencies tunnel diode amplifiers are advantageous only at frequencies above 5 Gc/s. Tunnel diodes give a noise figure of 4 to 4.5 db at optimum design. A major cost item of tunnel diode amplifiers is the circulator which serves to direct the input signal to the amplifier, and the output signal from the amplifier (which leaves through the same port it enters) to the mixer. The tunnel diode amplifier costs $1600 to $2000 depending on frequency.

Uncooled Parametric Amplifiers

The high cost of parametric amplifiers is due both to the high cost of components, and the amount of detail which must be considered in assembling them. The major cost factors are the circulator, the high quality diode which is used as the variable reactance and the pump.

To realize the potential noise figure of any low noise device, the surrounding components must be of good quality, and the contribution to the overall noise figure from the succeeding stages must be negligible. This places stringent requirements on certain associated parameters such as the signal loss in the circulator and waveguide and the noise figure of the succeeding stages. The present limitation to the noise figure which can be obtained with parametric amplifiers is the quality of the diode. The resistance in series with the variable capacitance sets the lower limit of the noise figure.[1] This will be considered the optimum noise temperature of paramps by 1970. To realize this noise temperature, a low noise mixer configuration or amplifier must follow the paramp.

This optimum design paramp will be more expensive due to the requirements on the associated equipment.

An alternative to the optimum design paramp is a less expensive paramp very similar to present models. Improvements in varactor diodes, pump sources, and circulator loss will lower the noise figure considerably.

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[1]The quality of varactor diodes is expressed quantitatively in terms of the cut-off frequency of the diode. Experimental diodes with an 800 Gc/s cut-off frequency have been built. By 1969 or 1970, diodes with a cut-off frequency of 1000 Gc/s will be available. The potential noise figure or potential effective temperature of the parametric amplifier is determined by the cut-off frequency, and with a cut-off frequency of 1000 Gc/s an effective temperature of 35°K at .2 Gc/s is possible.

Cooled Parametric Amplifiers

The major cost item of cooled parametric amplifiers is the refrigerator. Two currently used refrigerators cool to temperatures of 20°K and 4.2°K. The 20°K refrigerator costs $20,000 while the 4.2°K refrigerator costs $80,000. The refrigerators require service about three times a year. During the service period the receiver would be "down" for 12 to 24 hours. With the purchase of additional parts which can replace the parts which are being serviced, this down time can be reduced to 4 hours. The additional cost would be $2400 for the 20°K unit and $10,000 for the 4.2°K unit.

The cost to build the paramp itself is much higher for the uncooled case. The cost of the paramp alone for the 4.2°K unit is $120,000 and $25,000 for the 20°K unit.

Besides the basic paramp and refrigerator units, metering equipment is also needed to monitor the operation of the amplifier and the status of the refrigerator. Combining all costs which must be considered, the cost of a cooled paramp is high--$40,000 for the 20°K unit and $240,000 for the 4.2°K unit. The effective receiver temperatures which are obtained at this price are listed as a function of frequency on Figure 3.3.3.

3.4 COST OF MODULATION IMPROVEMENT (C_I VS. I)

3.4.1 General

As previously mentioned, it is sometimes difficult to separate that cost of a receiver which is directly associated with noise figure from the cost to obtain a certain modulation improvement. The best example of this is the fact that improvement systems are invariably wideband with respect to the baseband. The improvement can be thought of as a power-bandwidth trade-off. It is much more difficult to obtain a certain noise figure in a wideband receiver than a narrowband receiver. Usually there is a bandwidth threshold--expressed as a percentage of the band center frequency--beyond which different design techniques are used, and this leads to an increased cost.

In the frequency range under consideration (100 Mc/s to 12 Gc/s) there are considerations other than cost which limit the bandwidth to be used in a satellite television system. Of particular importance are the allocation and spectrum utilization problems. It is practical to assume a certain bandwidth limit. It is assumed herein in discussing modulation systems, that a 5 per cent per channel bandwidth limitation is reasonable. No modulation system is considered which will require a bandwidth B greater than 5 per cent of the operating frequency (f_c). It will be further assumed that a bandwidth selection within this relatively narrow limit will not influence noise figure cost. Above 1 Gc/s, a 50 Mc/s system is less than 5 per cent of the center frequency.

In the discussion to follow, it will be shown that for most frequencies other limitations will occur before the bandwidth limitation.

In determining cost versus improvement factor (C_I vs. I), it is first necessary to compare the different available modulation systems and to choose the type of modulation system which will give a particular improvement at a minimum cost. This cost then represents the minimum cost for a specified improvement.

Appendix C presents a comparison of PCM and FM for application to satellite television. It is proven that FM is the most economical system.

The FM improvement is given by the relation

$$(S/N)_o = 3M^2 \; (S/N)_{RFb} \qquad 3.4.1$$

where M is the modulation index and $(S/N)_{RFb}$ is the pre-limiter signal-to-noise considering only the noise in the baseband b. The total RF bandwidth is

$$B_{RF} = 2 \; (1 + M)b \qquad 3.4.2$$

It is shown in the appendix that

$$(S/N)_o = (3M^2 + 3M^3) \; (S/N)_{in} \qquad 3.4.3$$

This defines the modulation index to be used for a given signal-to-noise threshold $(S/N)_{in}$ where $(S/N)_{in}$ includes the noise in the total RF bandwidth.

3.4.2 FM Improvement Characteristics

Equation 3.4.3 gives the value of modulation index (M) which will give maximum improvement for a desired output signal-to-noise ratio for a given threshold, while Equation 3.4.2 gives the necessary bandwidth. These relations are shown in Figure 3.4.1 along with the 1.5 M^2 improvement curve. In using Figure 3.4.1 the top curve showing $(S/N)_o/(S/N)_{in}$ should be used with the values on the left ordinate scale. The lower curve showing $(S/N)_o/(S/N)_{RFb}$ should be used with the ordinate scale on the right. The abscissa scales showing modulation index and RF bandwidth B are common to both curves. For a given $(S/N)_o$ to $(S/N)_{in}$ threshold ratio the modulation index, which corresponds to maximum improvement, can be determined using the top curve. From this value of modulation index the maximum modulation improvement can be determined using the lower curve. All values used on the ordinate scales in this Figure are ratio values, not db.

For a standard FM receiver with a 12 db threshold (ratio of 15.8) and a desired output of 32.3 db[1] (ratio of 1.70 X 10^3) the improvement ratio is 107.2 or 20.3 db. The associated modulation index and improvement factors are 3.03 and 14.0 (expressed as a ratio), respectively. If threshold reduction techniques such as a phase-locked loop or frequency modulation feedback are used, a lower threshold and greater improvement can be realized. The current threshold limit which has been reached is 4 db. However, it will probably be 1970 before this threshold is consistantly realized. Stability problems in the feedback loop make current

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[1]A television signal to triangular noise ratio of 32.3 db will give the same quality picture as a signal-to-flat noise ratio of 40 db. FM can be considered as also providing a noise weighting improvement of 7.7 db or 6.0.

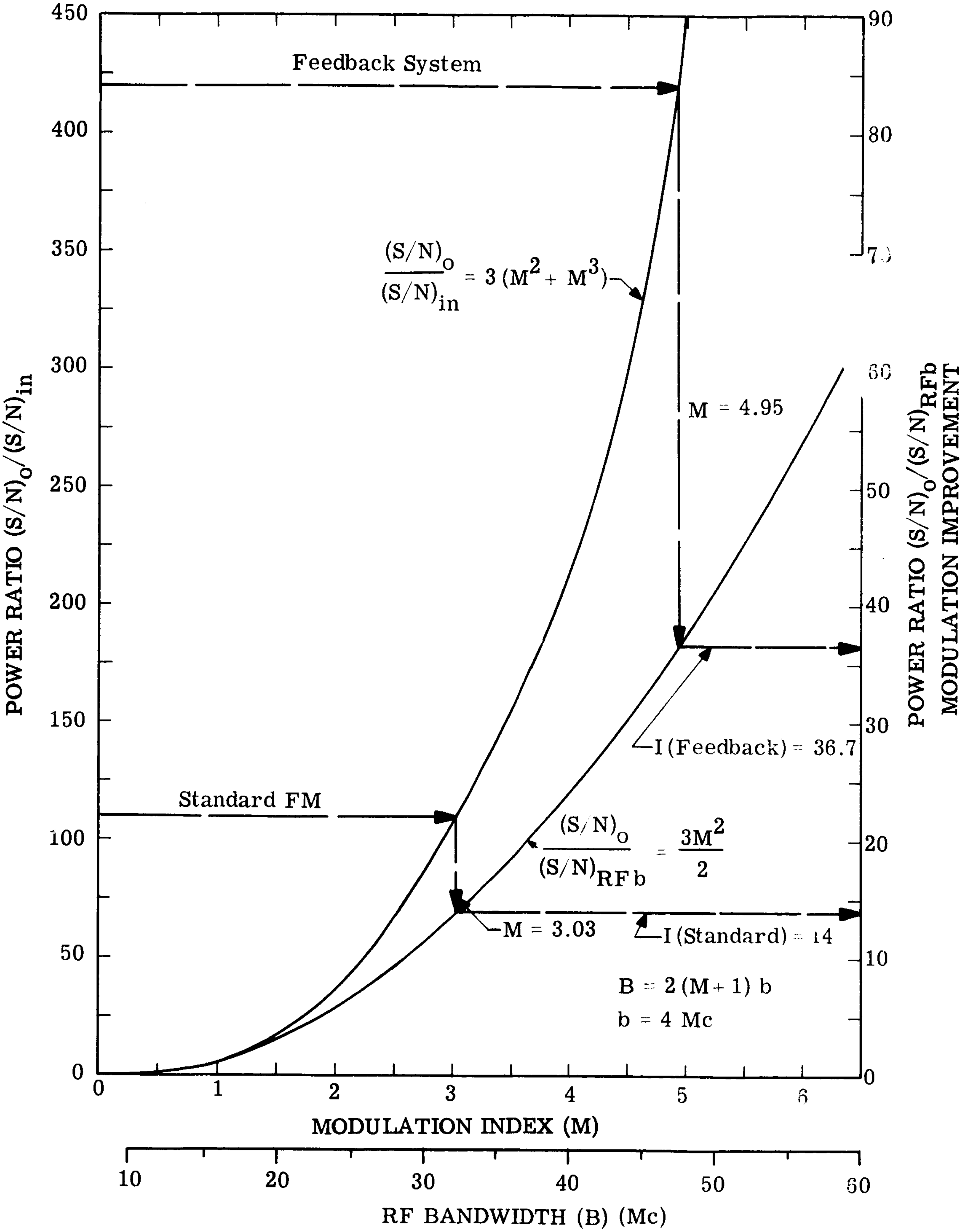

Figure 3.4.1. Summary of FM Considerations for Satellite TV.

systems quite complex and in some cases undependable. There is a second threshold effect which should be considered at this time and that is the threshold at which the output noise spectrum is no longer triangular. This threshold is about 6 db at which point intermodulation occurs and the low frequencies in the output are filled with the intermodulation noise and the FM noise weighting improvement is not so great. For this reason a threshold of 6 db will be associated with the phase locked loop systems.

The improvement for the 6 db threshold is determined from Figure 3.4.3 by starting at 32.3 db - 6 db = 26.3 db or 427 on the $(S/N)_o$ to $(S/N)_{in}$ threshold axis; the modulation index and improvement factor(s) are 4.95 and 37.0, respectively.

The total improvement in using FM is then the product of the modulation improvement factor and the noise weighting improvement which is 14 x 6 = 84 for a standard FM system, and 37 x 6 = 222 for a feedback system.

The cost of the intermodulation improvement will include the cost of the IF amplifiers, limiter-discriminator and the feedback loop for the threshold reduction case.

For the standard FM system, the cost can be established by relating the cost of the needed components to the cost of stages of a mass-produced UHF or VHF tuner. In mass production the cost of tuners can be calculated on the basis of a cost of $2.00 per stage. The standard FM receiver is fairly uncomplicated and this method of cost estimating should be very accurate for quantities of a million. The standard FM system would require three IF amplifiers and a limiter-discriminator stage.

The receiver manufacturer's cost would be $8.00 and the purchase price about $32.00. If this is projected back on an 85 per cent learning curve to a quantity of one, the cost would be $843.

Estimates on the cost of a feedback system in mass production vary widely. It was felt that the extreme linearity requirements in the feedback loop and other system parameters, which must be closely controlled, would limit the reduction in cost which comes from mass production. A fairly safe estimate would be about $90.00 purchase price. When extended back on an 85 per cent learning curve, this becomes $2,370 for a quantity of one. At present the cost of a feedback system would be considerably higher due to the fact that a great deal of engineering effort is used in the development of a feedback system. By 1970, the characteristics of FM feedback systems will be much better known and their design standardized. The cost of a single unit will go down due to this.

3.5 COST VERSUS RECEIVER ANTENNA AREA (GAIN) (C_A VS. A_R)

3.5.1 General

Arriving at a cost versus performance function for antennas that could be used in a system for receiving a television signal from a stationary satellite may be approached from several directions. For purposes of solving the one-way transmission equation, the ideal way to present cost information on antennas would be to plot antenna cost versus antenna effective receiving area. However, the realities of antenna design and utilization throughout the frequency range of interest dictates that gain be the primary performance characteristic of an antenna. Gain and effective area are related by the relationship $G = \frac{4\pi A}{\lambda 2}$, where A is the effective aperture and λ is wavelength. Wavelength λ is equal to

C/f where C is velocity of electromagnetic waves in space and f is frequency. The fundamental cost data have been developed as a function of antenna gain.

3.5.2 Antenna Types

In the frequency range 0.1 to 12 G/s, a great diversity of antenna types may be used. This results from the fact that the wavelengths of the frequencies under consideration vary from relatively large, 3 meters, to fairly small, 3 cm, magnitudes. The size of the wavelength determines the best mechanical structure which may be used for efficiently capturing the desired signal. At the lower frequencies, 100-900 Mc/s, it is more efficient to use Yagi-like structures, having elements spaced appropriate fractions of wavelength apart, while at the higher frequencies the small wavelengths permit a parabola of mesh of spun aluminum to be more efficient.

Although the Yagi and parabola are the two major types of antennas used, there are a number of hybrids which have been developed for special purposes and may prove feasible for this application. These include cylindrical parabolas, reflectarrays, and disk rods. Figure 3.5.1 gives an indication of the types of gains which may be achieved at different frequencies with a variety of presently available antennas. The largest antenna represented is a fifteen-foot parabola, as this is a break-point for antennas of relatively simple construction. However, this does not preclude consideration of larger antennas. The antennas in this figure are representative of the median quality antenna in each category, since it is unrealistic to consider the highest quality antenna available. However, it is important to evaluate the relationship

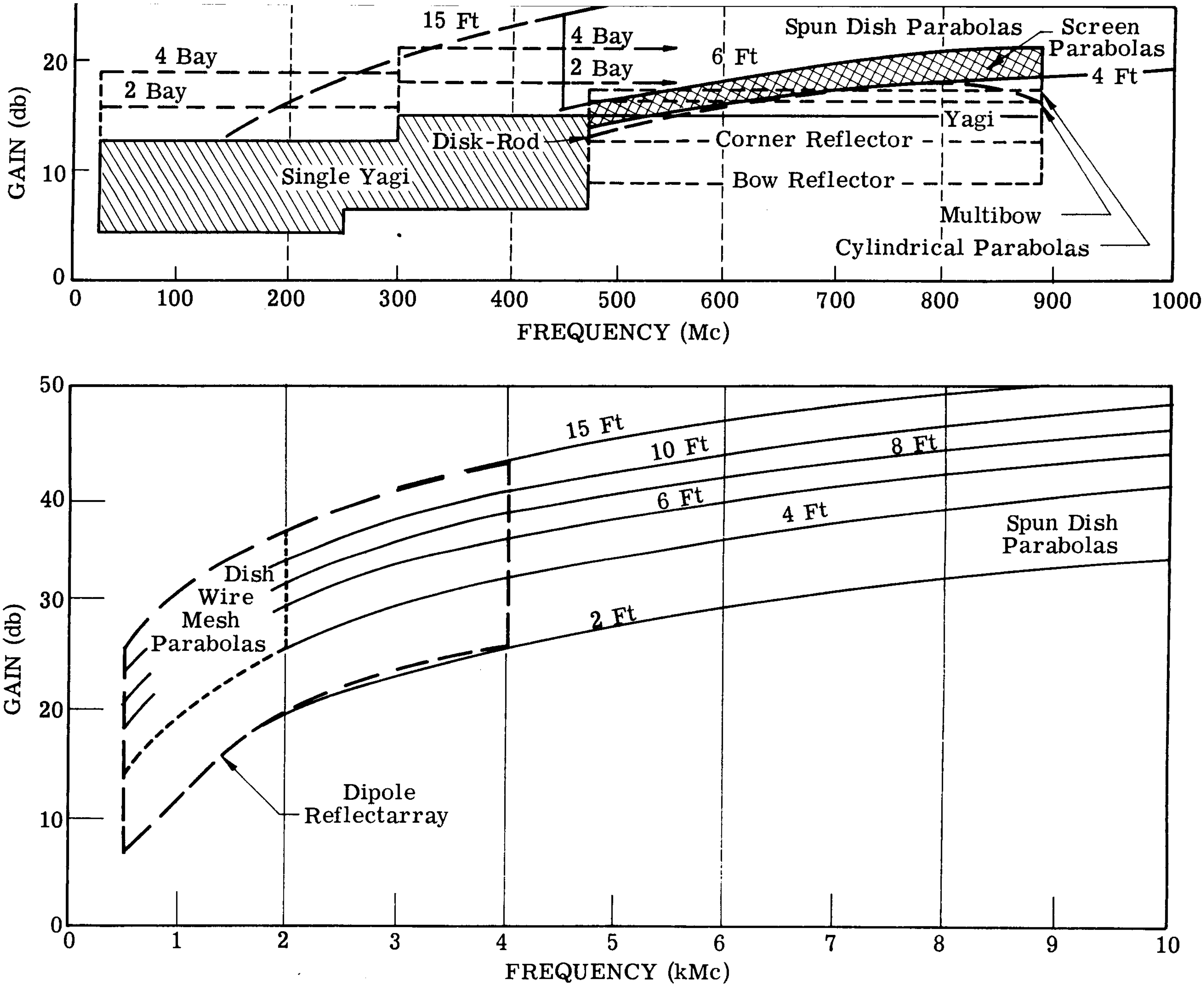

Figure 3.5.1. Frequency Versus Gain for Different Types of Antennas.

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between cost and the different antenna parameters which determine quality. For example, the performance of a parabolic antenna may be influenced by type of feed, blocking factor, and dish tolerance; but to achieve high efficiency, low blocking and tight tolerance may be very costly and not really necessary.

Therefore, this study has endeavored to ascertain the "break-points" in the cost versus quality relationship which will give maximum quality for the least amount of cost.

3.5.3 Antenna Quantity

Another major area of investigation important to evaluating cost, besides quality and type of antenna, is quantity. The variables to be considered here are: type of antenna, material of construction, and demand. In other words some types of antennas (such as the Yagi) presently being manufactured for home consumption, are already being made on a mass-produced basis. Quantity versus cost for different antennas is shown in Figure 3.5.2. The cost of Yagi and other types of single antennas used for VHF or UHF are shown as a family of parallel straight lines at the bottom of the Figure. The different lines account for antennas of different gains. The cost of these types of antennas would not appreciably decrease if they were mass-produced in greater numbers. On the other hand, very large antennas costing hundreds of thousands of dollars for one would realize an appreciably large percentage decrease in cost if they are made in quantities of tens and hundreds. However, this large percentage decrease will level-off somewhere between one hundred fifty and two hundred. This trend is particularly noticeable for smaller parabolas, 2-15 feet in diameter, where there is only a small percentage

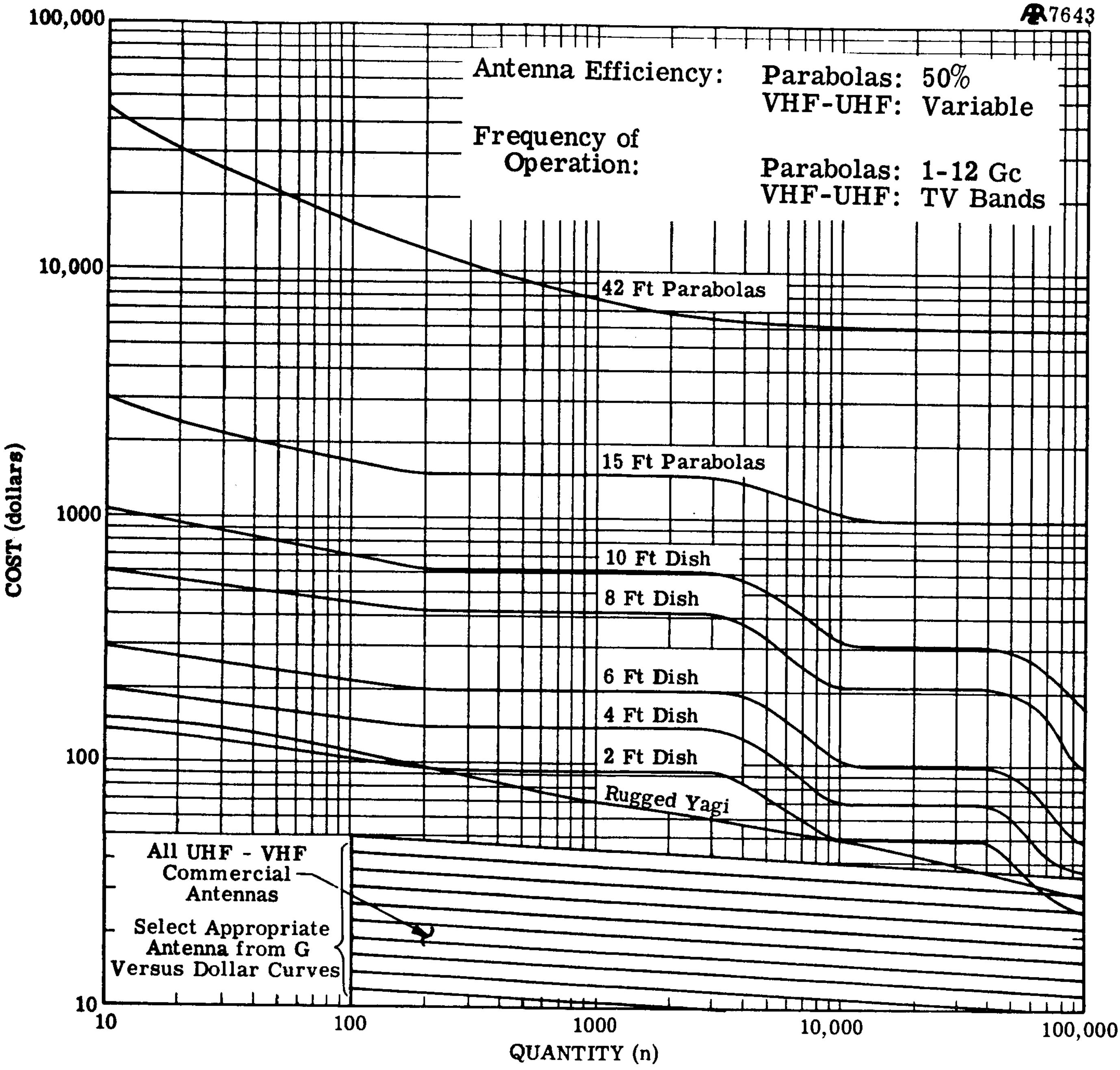

Figure 3.5.2. Antenna Cost Versus Quantity.

decrease in the cost for quantities between one and one hundred fifty, and constant cost after two hundred.

The cost breaks for different quantities may be explained by differences in manufacturing processes. If antennas are made in small quantities, they are virtually custom made for a particular purpose. When several hundred of a particular type are made, a certain amount of mechanized mass production is possible, but it is still too costly to invest in a dye-cast or elaborate molding process. Most "standard parabolas" are in this category, and are made from "spun" aluminum. This explains why the cost of parabolas manufactured in hundreds have a cost leveling at one hundred fifty.

Not until demand indicates a requirement for manufacturing thousands of antennas will there be a major cost break. The demand for thousands will permit the investment in automated mass-produced techniques which will result in an appreciable decrease in cost per individual antenna. For example, two-foot parabolic antennas could probably be stamped out at a cost of $.25 apiece. Such stamping techniques are already being employed in the home television antenna industry; consequently, added demand in this area would not effectively decrease the present cost per item. In general, as demand increases, the percentage of an antenna cost reflecting development and labor decreases, and the final limitation is determined by cost of material. Therefore, it is not until parabolas are made in thousands that plastic becomes feasible.

3.5.4 Gain Versus Cost Curves

The basic gain versus cost curves are plotted in Figures 3.5.3, 3.5.4 and 3.5.5. The data on these curves were derived from

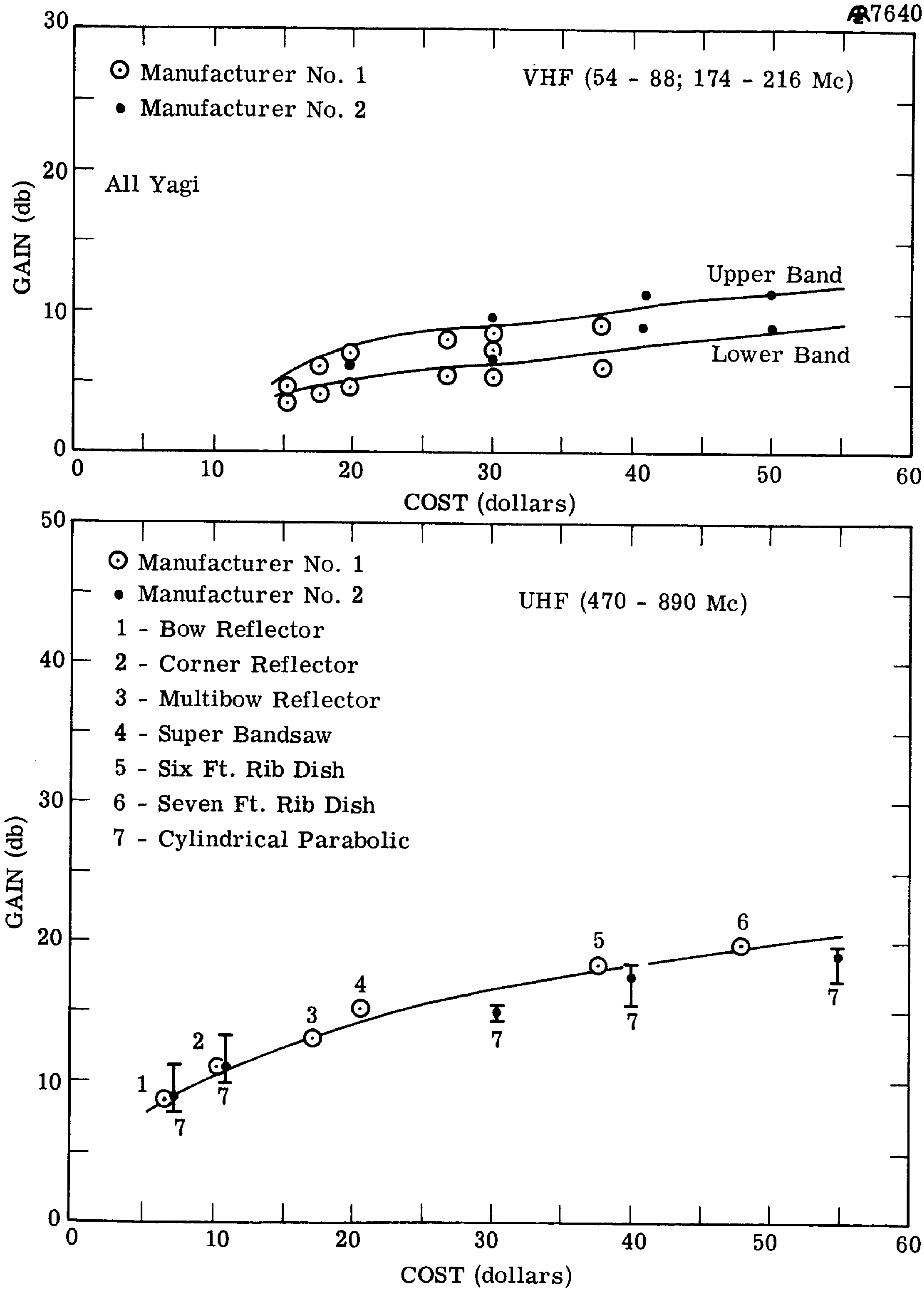

Figure 3.5.3. Cost Versus Gain for Broadband Small Antennas.

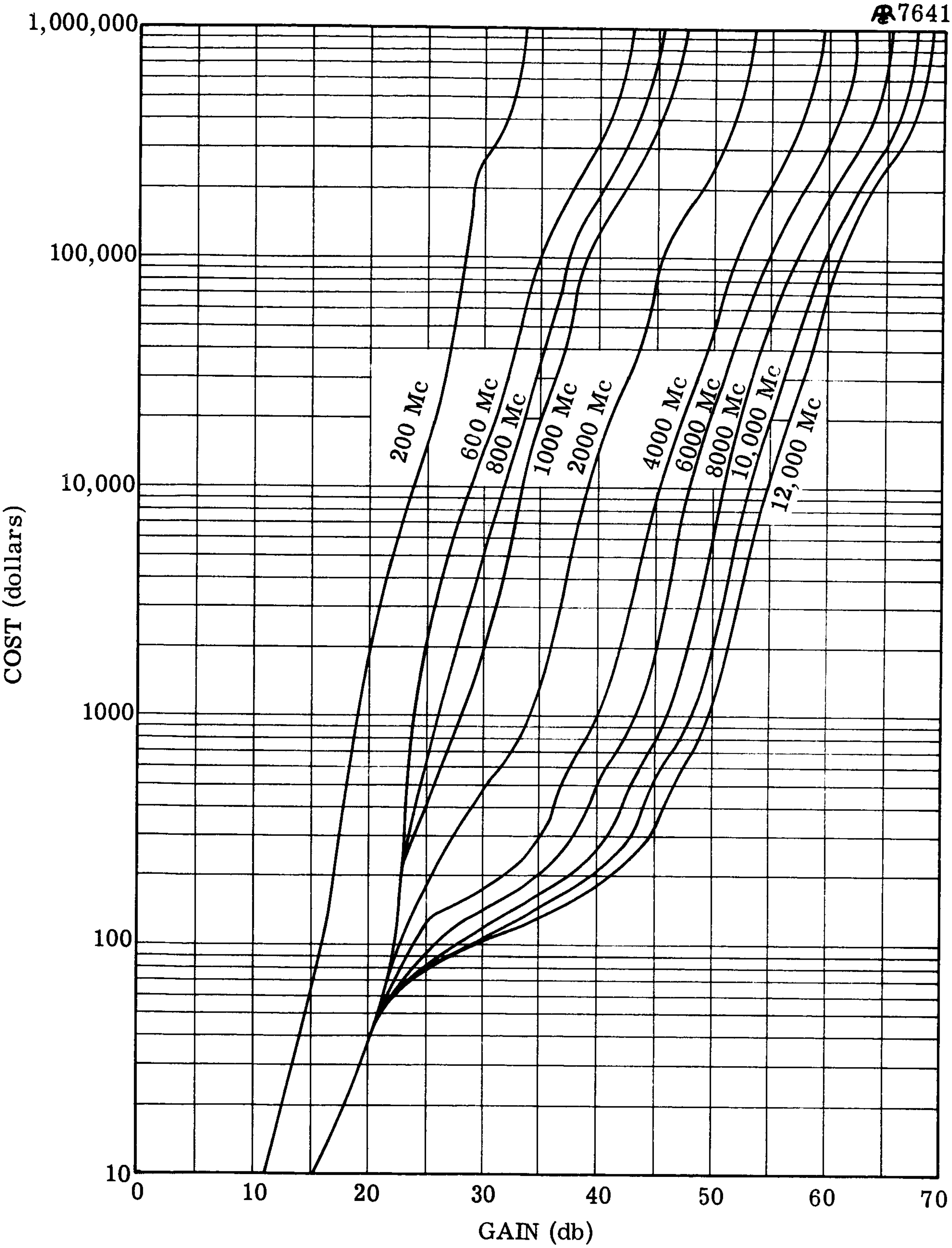

Figure 3.5.4. Antenna Gain Versus Cost at Different Frequencies for Quantities of 1 - 10.

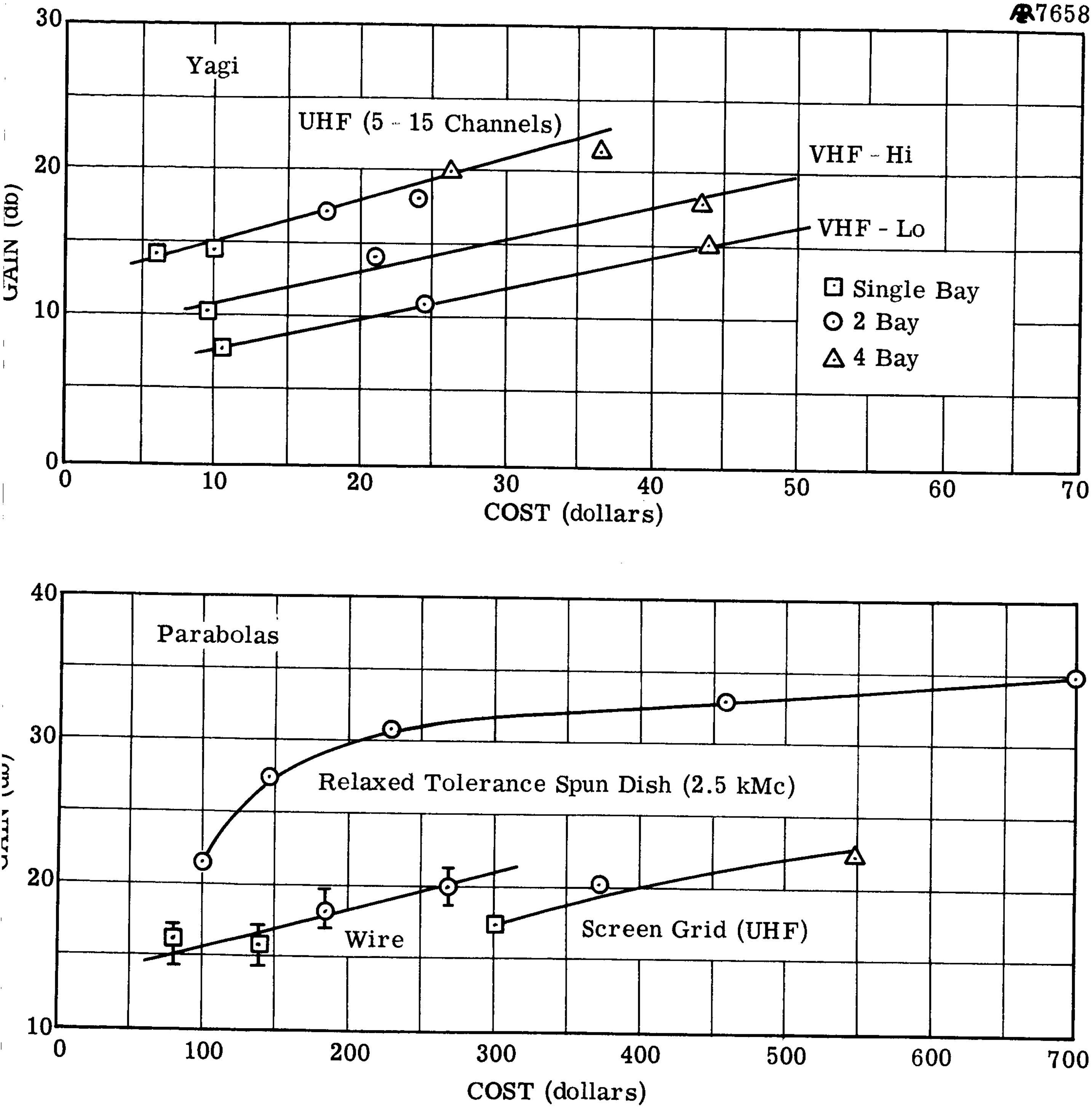

Figure 3.5.5. Cost Versus Gain for Narrowband Specialized Antennas.

information obtained from over ten major manufacturers of antennas. No point on these curves was determined solely on the basis of information obtained from one manufacturer.

The top figure in Figure 3.5.3 shows a set of graphs depicting the cost function for presently available broadband antennas in the VHF frequency regions. The highest gain feasible in the upper VHF band using a single antenna is 15 db. This would be considerably higher in cost than shown in Figure 3.5.3. In this band the Yagi construction gives the best gain for the price paid. There are various "V" types of antennas available; however, they evolve principally for use in urbanized areas having strong television signals from local stations. They present little more than a 0 db termination to the transmission line, and consequently, may be ruled out for satellite application, as there are antennas of comparable cost which provide appreciable gain.

In the UHF band the wave lengths are such as to permit optimization of the Yagi technology for television reception. These frequencies, and especially the higher ones, are particularly well suited for getting the largest gain/dollar ratio for receiving antennas available in the present commercial market. This is evidenced by the bottom figure in Figure 3.5.3. The points on this graph show not only wide variation in gain/dollar ratios, but also in type of antenna configuration. The configurations include bow and corner reflectors, Yagi, and cylindrical and circular ribbed parabolas. All of these antennas, as well as all of the VHF antennas in the Figure above, are constructed so as to provide reception over the entire frequency band in which they operate, i.e., VHF-low, 54-88 Mc/s; VHF-hi, 174-216 Mc/s or UHF, 470-890 Mc/s. In order to do this, performance sacrifices have been made to obtain a relatively constant gain over the entire band. However, because of the physics of antenna design, this is impossible to achieve; therefore, the gain figures on these graphs represent median values (that is, the average gain across the band and not the gain at the middle frequency). The variation in this median value is ± 1.5 db, with the highest gains being obtained at the highest frequencies.

The complete picture of the relationship between antenna gain, cost and frequency is presented in Figure 3.5.4. The curves in this Figure were derived for the optimum gain/cost ratio for each frequency. The type of antenna employed at a particular frequency to obtain a particular gain may vary. In general the low values at the low frequencies are for Yagi type, and the values for the higher frequencies are for parabolas.

3.5.5 Parabolas

The theory and design practices for the parabola, in contrast to the Yagi, are very well understood. Consequently, the present state-of-the-art of parabolas includes a number of sophisticated antenna systems which have optimized the performance of a parabola for a particular application. The majority of these applications are military and have demanded tight, expensive, performance specifications. The factors which must be specified when designing a parabola, which are critical insofar as determining ultimate cost, are listed in the following table, along with comments on the relevance of their design importance:

PARABOLA CHARACTERISTICS

Gain:	Will determine amount of transmitter ERP and is dependent on a number of other design factors.
Feed:	The most important design consideration, as it will determine the nature of the current distribution over the parabolic surface, and ultimately the maximum obtainable gain.
Efficiency:	Dependent on current distribution and directly related to gain; the less efficient, the less gain; average efficiency and easily obtainable is 50 per cent.
Side Lobe Level:	Important when antenna is located in noisy environment, since this characteristic may severely increase the noise temperature of the whole system and impair the antenna performance, thereby necessitating an increase in transmitted satellite ERP.
Blocking Factor:	Determined by feed configuration; contributes to system losses, and increases noise temperature of antenna.
Antenna Temperature:	Is extremely important as noise temperature of receiver approaches that of antenna; T_A becomes the limiting factor.
Frequency:	Determines the requirements for dish tolerances, and consequently the method of parabola construction: spun aluminum, wire mesh, honeycomb plastic-aluminum or aluminum tubing. The lower the frequency, the less stringent the tolerance, but the higher the frequency the greater the obtainable gain with a fixed diameter antenna.

In view of the above considerations the following observations are relevant based on investigations carried out in this study:

1. The tolerances necessary for a 50 per cent efficiency are easily obtainable with present technology. Once the desired electrical properties of an antenna have been determined, there will be little deviation in the performance characteristic of an antenna produced in large quantities.

2. The break-point between the use of a Yagi structure and some type of parabola is in the 800-900 Mc/s region. After this, wire or mesh parabolas are used through 3000 Mc/s, and spun aluminum dishs from this frequency through 12,000 Mc/s.

3. The types of feeds include dipoles, waveguides, and numerous horn types; notably, the cassegrain, reflector and hog(offset feed). The slot dipole feed is the best solution at frequencies in the range 800-3000 Mc/s, while a waveguide feed is most suitable for frequencies above 3000 Mc/s. Both of these feeds have a relatively simple construction and will more than meet the required performance specification. In other words, these two types of feeds are the types which best lend themselves to mass production. The horn-type feeds are most suitable for specialized applications, and best used in conjunction with a large, more sophisticated receiving system requiring a very low antenna noise temperature. Different horn feed antennas are compared on a relative basis in the Table below:

Type	Antenna Temperature (T_A)	Gain/Dollar (G/$)	Gain/Antenna Noise (G/F_A)
Multiple horn	20-30°K	Excellent	Poor
Horn refl.	~ 0°K	Poor	Excellent
Cassegrain	~ 10°K	Fair	Good
Hog horn	~ 5°K	Good	Fair

3.5.6 Polarization

Faraday rotation causes the plane of polarization of a wave traveling through the ionosphere to change its orientation relative to the antenna from which it was transmitted, thereby causing an uncertainty as to the polarization of the wave to be received. As a result, unless certain precautions are taken, the desired signal may be completely lost.

At high frequencies, 1,000-2,000 Mc/s and above, the Faraday rotation effect may be neglected. However, below these frequencies there is a possibility of losing from 3 db to the entire signal, depending upon the polarization of the transmitting and receiving antennas. In the event that polarization considerations become important, the Table below is a guide to the utilization of the four polarization combinations.

TYPE OF POLARIZATION		COMMENTS ON UTILIZATION IN SYSTEM
Transmitter	Receiver	
Circular	Linear	Cheap and reliable; at most 3 db loss; requires no change at receiver.
Linear	Linear	Cheap, but possibility of losing 100 per cent of signal.
Circular	Circular	Expensive, less possibility of 100 per cent loss but could happen.
Linear	Circular	Same performance as first above, but much more expensive.

The above chart of relative comparisons indicates that the optimum system would probably use a circularly polarized antenna in the satellite and a linearly polarized antenna on the ground at the frequencies below 1,000-2,000 Mc/s, as the other configurations are either too unreliable or too expensive.

3.5.7 Different Parabola and Yagi Configurations

The graphs in Figure 3.5.5 indicate the cost versus gain relationships for several forms of Yagi and parabolic antenna configurations which appear to be particularly useful for the application under consideration. The first graph indicates what can be achieved with stacked Yagis operating in the TV bands; the second shows what can be achieved by (1) a relaxed tolerance spun dish, (2) a wire parabola, and (3) a cylindrical parabola.

It is possible to obtain a higher gain-to-cost ratio with the Yagis indicated in this graph because there has been a sacrifice in total bandwidth. The parabolic structures have tolerances which are all lower than what might be obtained from the usual parabolic dish, but have not been sufficiently degraded to impair reception of a TV signal from a synchronous stationary satellite. The end result is a higher gain to cost ratio.

3.5.8 Novel Antenna Designs

The discussion thus far has centered on antenna systems which are readily available and well understood in terms of price and performance. However, to take account of the 1970 time period, the investigations in this study have encompassed the application of newly developed antenna systems such as reflectarrays, printed circuit arrays, and disc-rods. Therefore, at this point the discussion will digress to analyze these possibilities. The cost versus gain characteristics of some of these are indicated in Figure 3.5.1, referred to earlier.

The reflectarray is an interesting possibility because of its relative simplicity of construction and reliability. Because it has a flat configuration, it could be easily incorporated into the structure of a building. In large quantities cost could be appreciably reduced. At present, since there is considerable expenditure in developing the proper phasing of its elements, the cost is high for small quantities. The limit on the cost is determined by the material, as the basic configuration consists of strings of aluminum dipoles strung together with proper phasing. The reflectarray has performance characteristics similar to a parabola having the same area. The best region of operation is 900-3,000 Mc/s. This antenna's liability is that it is very frequency sensitive which could hinder its usefulness.

The disc-rod is basically a Yagi-type structure. Its principal advantage would be to provide an inexpensive method of providing circular polarization plus high gain at the upper UHF frequencies. This antenna, and antennas of similar configuration, lend themselves easily to mass production.

Finally, there is work presently being done in the area of a phased array printed circuit antenna. This work has been initiated under the impetus provided by contracts for the large Air Force phased array antenna, AN/APX-85. The technology being developed under this program has great promise for revolutionizing the commercial antenna field, and its implications and applications should be further analyzed.

3.5.9 Cost Minimization Applications

As is explained in Section 4, a computer program has been developed to optimize component selection and receiving system characteristics to minimize the cost required for a receiving station at pertinent frequencies throughout the frequency spectrum of interest. The primary antenna inputs for this program consists of two matrices. The first indicates the variation of gain at the selected frequencies; and the second, a variation in cost at the selected frequencies. The points in the two matrices have been correlated. Again it should be pointed out that the points in these matrices have themselves been optimized for gain versus cost; and therefore, are valid inputs for obtaining a minimum cost receiving station for television.

3.6 COST VS. FEED LOSS (C vs. L)

3.6.1 General

The third major element in the receiving station, in addition to the antenna and the receiver, is the means used to connect the two. This may take the form of: (1) 300 ohm twin lead; (2) coaxial cable (polyethylene dielectric, heliax foam dielectric, heliax air dielectric, etc.); (3) rigid transmission line; or (4) waveguide. The particular type of feed used depends on the performance quality desired, frequency, and the particular application. For example, in a situation demanding high quality, using microwave frequencies, with the distance between the antenna and receiver relatively small and unencumbered, the optimum solution may demand the use of waveguide. However, if the distance between antenna and receiver were great, or a number of obstacles had to be circumvented, some type of coaxial cable would provide a better solution.

3.6.2 Cost Versus Attenuation

The performance versus cost characteristics for the different types of feeds are presented in Figure 3.6.1. These curves were generated from data obtained from reliable manufacturers of the pertinent feed types. The curves shown are "best fit straight lines" to actual data points relating cost to attenuation. Enough data points were plotted to establish that a definite exponential relationship (a straight line on log-log paper) exists between cost and attenuation. This relationship prevails at all the frequencies within the spectrum of interest.

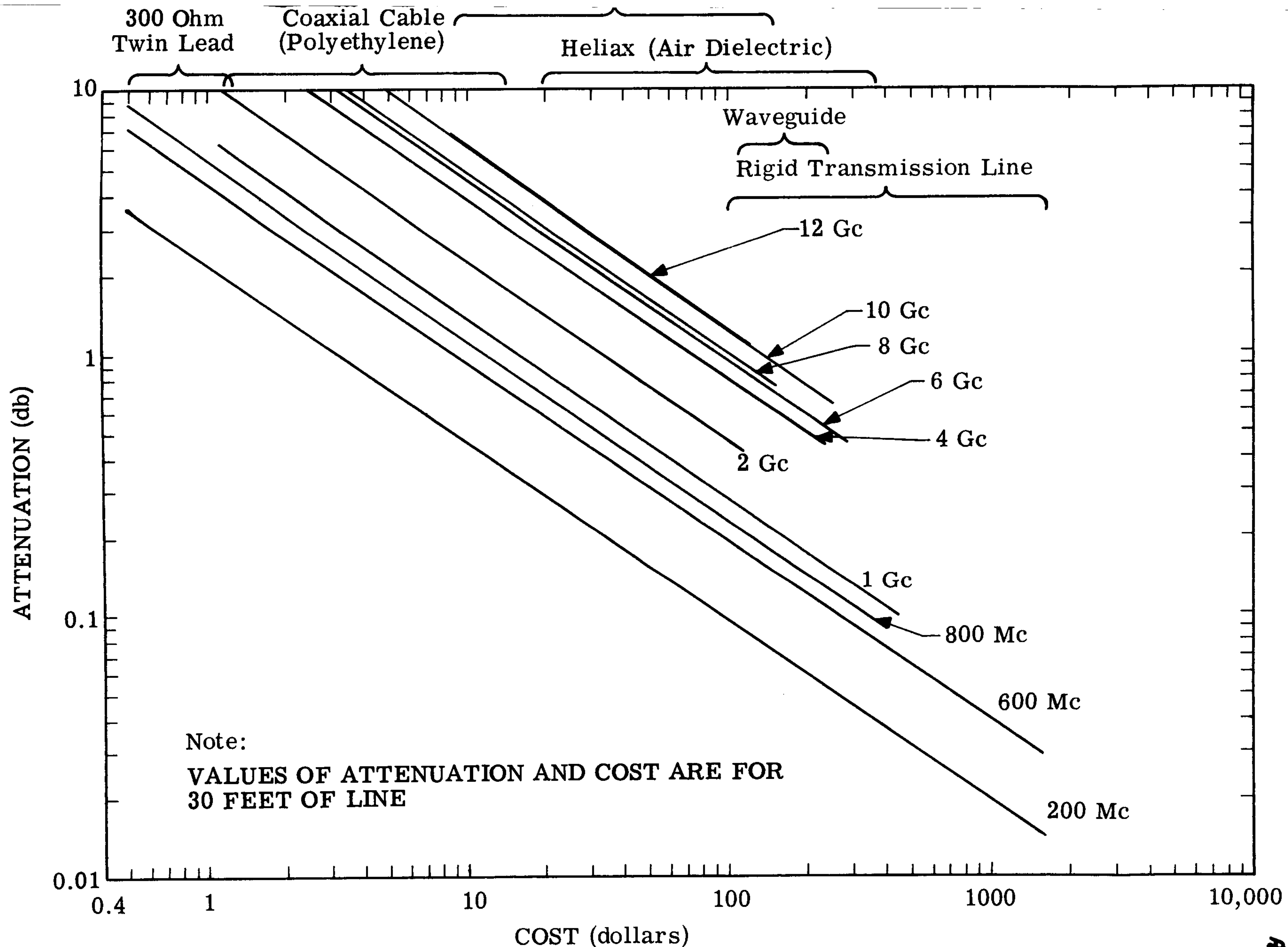

Figure 3.6.1. Cost Versus Line Loss, Based on Small Quantity.

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The attenuation calculations (computed for 30 feet of line) were based on the manufacturers' quoted values for each type of feeder line with the exception of 300 ohm twin lead. The attenuation values for twim lead, stated by the manufacturers, were for "new" line, without regard to increased attenuation due to installation. These values were appropriately modified to account for aging and increased attenuation due to environmental effects.

The cost of 30-foot sections of line was based on manufacturers' quoted retail prices for minimum quantity sales. Therefore, these costs represent the most expensive cases. In estimating costs for larger quantities, a 95 per cent learning curve may be used.

An important fact brought out by this compilation of cost versus attenuation data for different types of feeds is that the feed, regardless of type, will not contribute an appreciable amount of loss to the system except at relatively high frequencies. Therefore, the proportionate amount of dollars spent on the feed system should be small relative to the receiver and antenna. In other words, the expenditures of additional dollars in these latter areas will yield greater returns in terms of system performance.

These points are further illustrated in Section 4.0, which discusses the results of determining minimum cost systems at different frequencies.

4.0 RECEIVING STATION COST

4.1 GENERAL

For a specific satellite radiated power, there are many sets of receiving system parameters which would give a desired output signal-to-noise. If a low noise receiver is used with FM, a small required antenna gain may result from a solution of the system equation. Whereas, for the same ERP, if a poor quality receiver is used--a bigger antenna will be required. It is obvious that if a receiving station is to be selected for a given ERP, we are free to select a related parameter and pick that receiving station configuration which optimizes or minimizes, as the case may be, that related parameter.

For the receiving station, it may be desirable to minimize RF bandwidth, antenna size, or system maintenance.

For our purposes we will choose the minimum cost system for a particular ERP and frequency. There are two available methods to determine the minimum cost system.

The first is the brute force method of computing the cost for every workable system, and then selecting the system with the minimum cost.

The second is to analytically represent the cost function presented in Section 3, and then using the theory of maxima and minima with an imposed constraint, solve for the minimum cost configuration.

As a first attempt, the second method was used, but it was felt that the receiver cost functions did not lend themselves to analytical representations easily. This is due to the fact that they are discontinuous functions and have some wide deviations from any simple analytical representations. It was decided that the first method would provide the more accurate results. The environmental data from Appendixes A and B and the receiver parameter cost information from Section 3 were used with the system equation and the IBM-360 computer to determine cost versus ERP.

4.2 COMPUTER PROGRAM

The computer program is very straightforward. As is shown in the block diagram of Figure 4.2.1, the outmost loop in the block diagram increments frequency. After the frequency is selected, the system antenna polarization configuration is chosen with the associated mismatch loss.

An initial value of satellite effective radiated power (PT) is then selected. For each set of frequency, ERP, and mismatch loss, a minimum cost system and its cost are determined. This is done as is shown in the second half of the block diagram. For each set of F (frequency), L(feeder loss), and I (improvement factor), G_R (receiver gain) is determined from the system equation, using the values of environmental parameters for that particular frequency. The minimum cost configuration is determined by comparing the cost for each configuration with a minimum cost register (C_{TMIN}). If the system cost for a particular combination is less than the value in the C_{TMIN} register, the contents of C_{TMIN} are replaced with the cost of that system, to be compared with the cost of other systems. After the F, L, I loop has been completed for all combinations, the set of values for the minimum cost system is printed out.

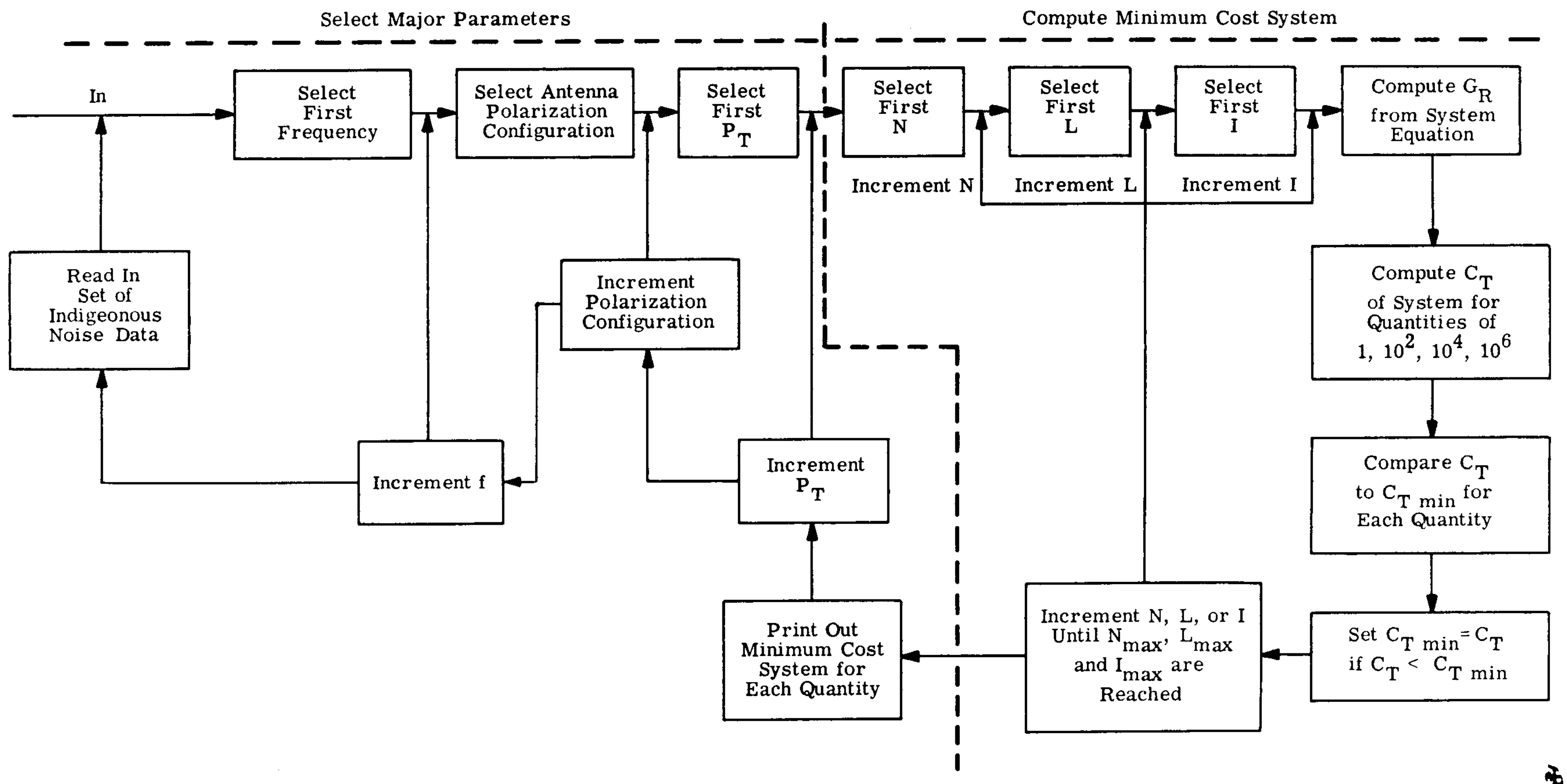

Figure 4.2.1. Block Diagram of Computer Program to Determine Minimum Cost System.

It should be mentioned that C_{TMIN} is determined for various quantity demands so that a system is determined for quantities of 10^6, 10^4, 10^2 and 1.

After C_{TMIN} has been determined for one set of selected values of frequency and satellite power the independent variables f and P_T are incremented.

The program is set up to give a complete output set for a specific indigenous noise level, and when this is completed, the computer reads in a different set of indigenous noise values and repeats the whole process.

4.3 INPUT PARAMETERS

4.3.1 General

The two major independent variables are frequency, satellite power. Values of frequency were selected to cover the frequency range under consideration with emphasis to those frequencies where broadcast bands are located. Satellite ERP values were selected to cover the range 30 dbw to 90 dbw in increments of 10 dbw with additional points at 45 and 55 dbw. From the system equation, it is seen that bandwidth and signal-to-noise ratio can be factored out. This will enable interpretation of the results for systems with bandwidth and desired output signal-to-noise which are different from those values used in the program, namely bandwidth = 4 Mc/s and $(S/N)_o$ = 40 db.

4.3.2 Input Environmental Parameters

Table 4.3.1 lists the values of frequency used in the program. Also listed are the values of the various environmental parameters for these frequencies and a θ of 47° corresponding to antenna elevation of 43°. Values for the environmental parameters are taken from the data presented in Appendixes A & B.

4.3.3 Input Receiver Parameters and Associated Costs

Values of F, L and I used in the program were taken from the data presented in Section 3 for the specific frequencies of interest.

Noise figure values for 200 Mc/s were taken from the VHF tuner data shown in Figure 3.3.1. For 600 Mc/s, 800 Mc/s, and 1 Gc/s, the UHF tuner cost information was used. Values for the remaining frequencies were taken from the corresponding curves for microwave receivers. Each illustrated data point on the noise figure vs. cost curves was used.

Improvement factor versus cost information used in the analysis is given in Section 3.4.2. Three types of modulation were considered for 800 Mc/s and above. These are vestigial (V), standard FM (F) and threshold reduction FM (T). At 600 Mc/s only V and F were considered, while at 200 Mc/s only V is considered.

In order to have a manageable number of possible system combinations, only four values of feeder loss (L) are considered. These values are evenly spaced over the loss vs. cost curve with the first point being the value for an antenna mounted RF amplifier with zero loss.

Antenna information was stored so that when G_R (the antenna gain) is computed, its cost may be determined from the stored information.

4.3.4 Relation to Television Reception

The amount of ERP radiated from the satellite determines the amount of field strength that will be present at a particular receiving station location. This field strength subsequently determines the magnitude of $(S/N)_o$ for a receiver. The quality of a television picture

TABLE 4.3.1

ENVIRONMENTAL INPUT DATA

FREQ. (Gc)	α	β	Q_N	Q_H	T_{TK} (°K)	MAXIMUM INDIGENOUS NOISE (URBAN) T_I (°K)	10% OF MAXIMUM INDIGENOUS NOISE (SUBURBAN) $.1\ T_I$ (°K)	NO INDIGENOUS NOISE REMOTE RURAL
.2	0	0	0	0	200.0	700,000	70,000	0
.6	0	0	0	0	13.0	38,000	3,800	0
.8	0	0	0	0	8.5	18,000	1,800	0
1.0	0	0	0	0	6.0	10,000	1,000	0
2.0	0	0	0	.008	4.0	1,600	160	0
4.0	0	0	.014	.063	4.1	256	25.6	0
6.0	0	0	.032	.199	4.3	90	4.0	0
8.0	0	0	.053	.402	5.0	42	4.2	0
10.0	0	0	.088	.636	5.5	23.4	2.34	0
12.0	0	0	.130	.826	6.0	15	1.5	0

is based upon the subjective judgment of the individual viewer. The best attempts to quantify the relation between receiver output S/N, and quality of picture was reported in the results of the TASO and New York City UHF Television studies. The $(S/N)_o$ required for a particular quality of signal can be related to a necessary field strength by taking into account receiving station characteristics. The picture quality criteria established in the TASO and New York City UHF Television experiments were used in the present analysis. The relationship between receiver output $(S/N)_o$ and quality of picture is tabulated below. A more thorough discussion of television standards is included in Appendix D.

Receiver Output (S/N)o (db)	Signal Quality	
	Grade	Description
44.5	1	Excellent; picture of extreme high quality
33.5	2	Fine; high quality; interference perceptible
27.0	3	Passable; acceptable quality; interference not objectionable
23.0	4	Marginal; poor quality; interference somewhat objectionable
17.0	5	Inferior; very poor quality; objectionable interference present
----	6	Unusable; so bad could not watch it

4.4 PROGRAM RESULTS

Figures 4.4.1 through 4.4.17 present the results of the program in graphic form. They illustrate the trend in cost versus ERP for the minimum cost receiver station. The specific values are for a desired output signal-to-noise ratio of 40 db and a bandwidth of 4 Mc/s[1]. These figures are for the video information only. The costs are for those primary components that affect $(S/N)_o$ as defined earlier in the report.

Figure 4.4.1 through 4.4.16 are for particular frequencies and for selected indigenous noise values corresponding to three types of environment. The indigenous noise values selected represent urban or city locations (maximum indigenous noise), suburban locations (assumed to be 10 db below urban), and remove rural (assumed to have no indigenous noise). The correlation between these indigenous noise values and the type location may not be exact for all cases, but use of these settings will provide a basis for evaluating the relationship between indigenous noise value and system cost. Four curves are plotted for each frequency and indigenous noise setting. These curves are for quantities of 1, 10^2, 10^4 and 10^6 receivers respectively.

On each figure the system configuration used for each data point is presented in a table. This shows the configuration which will give the desired output signal-to-noise at the minimum cost. The ERP at which the system configuration is specified is presented in the first column of the table, followed by the value of noise figure, type of modulation, antenna polarization system and antenna gain.

Symbols are used for conciseness in the tables to represent the following:

<u>Modulation</u>

V - Vestigial sideband or standard TV

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[1]Methods will be presented in Section 4.5 which will enable the interpretation of the figures for other values of bandwidth and desired output signal-to-noise ratio.

F - Frequency modulated TV

T - Frequency modulated TV utilizing threshold reduction techniques.

Antenna Polarization System

C - Circular polarization used at the transmitter and receiver

L - Linear polarization used at the transmitter and receiver

L_C- Circular polarization used at the transmitter and linear polarization at the receiver.

Results for Operation at 200 Mc/s

Figures 4.4.1 through 4.4.3 show the retail cost of the primary components of a receiving system as a function of satellite effected radiated power for the conditions of reception where there is no indigenous noise, 10 per cent of maximum indigenous noise, and maximum indigenous noise. Figure 4.4.1 shows the case for the no indigenous noise situation representing remote rural areas. Figure 4.4.2 shows the results for 10 per cent of maximum indigenous noise corresponding to suburban locations. Figure 4.4.3 shows results from maximum indigenous noise corresponding to urban locations. In all cases the retail cost of receiving systems as shown represents the cost of only those primary components which affect the signal-to-noise output of the receiver as related to noise input. It is these components which have been the exclusive concern of this study.

It can be seen from Figure 4.4.1 that with no indigenous noise the cost of receiving system components can be quite reasonable so long as high satellite power is used. The cost of receiving system components increases rapidly as satellite ERP is decreased below 60 dbw.

For the case of 10 per cent maximum indigenous noise as shown in Figure 4.4.2 and maximum indigenous noise as shown on Figure 4.4.3, the cost of receiving system components increases rapidly as the satellite ERP is reduced below 80 dbw and 90 dbw respectively. Thus, for urban and suburban areas satellite ERP's in the order of 80 to 90 dbw will be required if the cost of receiving system components is to be kept below $100. In fact, the results indicate that for high values of ERP, that is above 60 dbw in the no indigenous noise case and 90 dbw in the maximum indigenous noise case, reception would be possible for primary components costing less than $20 in quantities of a million. However, below these values of satellite ERP the cost of receiving systems rapidly increases to values in excess of $1000.

A significant reason for the increase in cost of receiving station components for values of satellite power below the critical values referred to above is the fact that modulation improvement systems, such as FM, are not considered feasible at 200 Mc/s. Thus, it is necessary to obtain necessary receiving station performance by increasing the antenna gain as satellite ERP is decreased. The gains required for values of satellite ERP below those discussed above are extremely high at 200 Mc/s.

There are two important reasons for considering only vestigial sideband for operation at 200 Mc/s. One of these is the fact that the bandwidth requirement would be greater than 5 per cent of the operating frequency if modulation improvement systems are used. The second reason and a very significant one is the fact that at frequencies as low as 200 Mc/s there is a bandwidth limitation caused by the ionosphere. While data available on the bandwidth limitations of the ionosphere are not as complete as desirable there is a sufficient amount of evidence to indicate that the bandwidth required for FM or other modulation improvement systems will be excessive. It appears that bandwidth must be limited to that required for vestigial sideband (VSB) if distortion in the ionosphere is to be avoided at 200 Mc/s.

Results for Operation at 600 Mc/s

The results for operation at 600 Mc/s are shown in Figure 4.4.4 through 4.4.6. As in the case of the results for 200 Mc/s, these three figures show results for reception at locations having no indigenous noise, 10 per cent maximum indigenous noise and maximum indigenous noise corresponding to remote rural areas, suburban areas and urban areas respectively.

The results for operation at 600 Mc/s are influenced very greatly by the fact that at this frequency, as was the case for operation at 200 Mc/s, there are large noise contributions from indigenous and cosmic sources. A factor of major consideration at frequencies in the order of 600 Mc/s is the effect of the ionosphere on permissible bandwidth. Available data leaves some reasonable question as to whether or not it will be feasible to operate modulation improvement systems such as FM at frequencies in the order of 600 Mc/s without significant distortion. Since the available data is not conclusive on whether or not such operation is feasible, the results of this study have assumed that FM will be possible but have also examined the situation if only VSB is feasible. Thus, in calculating minimum cost systems, the computer was programmed to evaluate the use of FM improvement relative to use of vestigial sideband as one of the component variables. In addition, to indicate the significance of the results where FM is considered desirable, curves have also been included to show the cost of receiving system components in the event that vestigial sideband is necessary to take account of the ionospheric bandwidth limitations of systems of wider bandwidth. For comparative purposes in those cases where FM would be the minimum cost system, the characteristics and cost of VSB are shown for comparative purposes (for no noise and maximum noise situations only). The cost of vestigial sideband in such cases is shown by dotted lines whereas the cost for the minimum cost system including the use of FM are shown in solid lines.

The results shown in Figures 4.4.4 through 4.4.6 indicate the possibility of using inexpensive vestigial sideband receiving station components for satellite powers that are above 60 dbw with no indigenous noise and above 80 dbw for maximum indigenous noise. This is similar to the results for operation at 200 Mc/s. Assuming that it is feasible to use FM improvement without serious limitation caused by the ionosphere, then the cost of receiving station components for reception under conditions of satellite ERP below the critical values just mentioned can be realized. It will be noted from the results of Figure 4.4.4 for no noise that receiving station component costs of less than $100 would occur for the use of FM and satellite ERP as low as 40 dbw. This would be the case for reception in remote rural areas where no indigenous noise would exist. For reception in urban areas with maximum indigenous noise, the satellite ERP required to permit reception using receiving components costing less than $100 would be a minimum of 60 dbw.

The importance of the location of receiving stations, and more specifically the value of indigenous noise experienced, can be realized from a study of the results shown for operations at 600 Mc/s. (Figures 4.4.4 through 4.4.6) An important contribution to the cost of receiving stations for powers below the critical values referred to above is the cost of the receiving station antenna necessary to achieve the required results, particularly in the presence of indigenous noise.

Results for Operation at 800 Mc/s

Figure 4.4.7 shows the results for locating maximum indigenous noise and no indigenous noise. Figure 4.4.8 shows results for 10% maximum noice. The same conclusion can be drawn for 800 Mc/s as for the 600 Mc/s case concerning the effects of noise on cost at different values of satellite ERP. For the no indigenous noise case, it becomes advantageous to use a low noise receiver at higher values of ERP than for the maximum noise case. A significant break in the cost versus ERP curves occur at the ERP where FM is used. For operations at 800 Mc/s, threshold FM is a modulation system possibility and becomes advantageous at about 50 dbw for the maximum noise case. It is noted, that the slope of the curve changes at this point also as it did for the FM case, but not in so pronounced a fashion. This change in slope is also related to the reduced antenna demands.

As discussed with respect to the results for operation at 600 Mc/s, there is a possibility that the ionosphere will cause some distortion to the use of bandwidths required for FM. However the danger at 800 Mc/s is less than at 600 Mc/s. This factor is discussed further in Appendix A.

Results for Operation at 1.0 Gc/s

The first section of the report shows the results for this case. Figure 4.4.9 compares the no noise case to the suburban case (10% maximum noise). Figure 4.4.10 shows the results for the maximum noise case. As can be seen, very little cost difference is shown at the higher ERP's from that determined for operation at the lower frequencies. However there is not as great a price increase for the lower ERP's as was determined for the lower frequencies. This is due to the smaller value of indigenous noise at this frequency. As the indigenous noise is reduced, it becomes more advantageous to use low noise receivers, such as paramps. This gives another parameter, beside antenna gain, which can be used to improve system performance, and permit operation at lower values of ERP.

Results for Operation at 2.0 Gc/s

Figure 4.4.11 compares the no noise case with the indigenous noise case at 2.0 Gc/s. No cost difference exists, for the two cases, above 55 dbw. Very little difference occurs for ERP's below 55 dbw. It should be noted that the curves in Figure 4.4.10 have a very steep slope. This is because at 2 Gc/s microwave techniques are used. Reduction in ERP may be compensated for largely by increased antenna gain.

Results for Operation on Frequencies 4.0 G/cs through 12 Gc/s

Figures 4.4.12 through 4.4.16 show the cost for operation at 4.0 Gc/s through 12 Gc/s in increments of 2.0 Gc/s. Above 2.0 Gc/s, the cost of the systems is independent of indigenous noise. System costs were computed for approximate values of noise, but this factor was found to have only a minute effect.

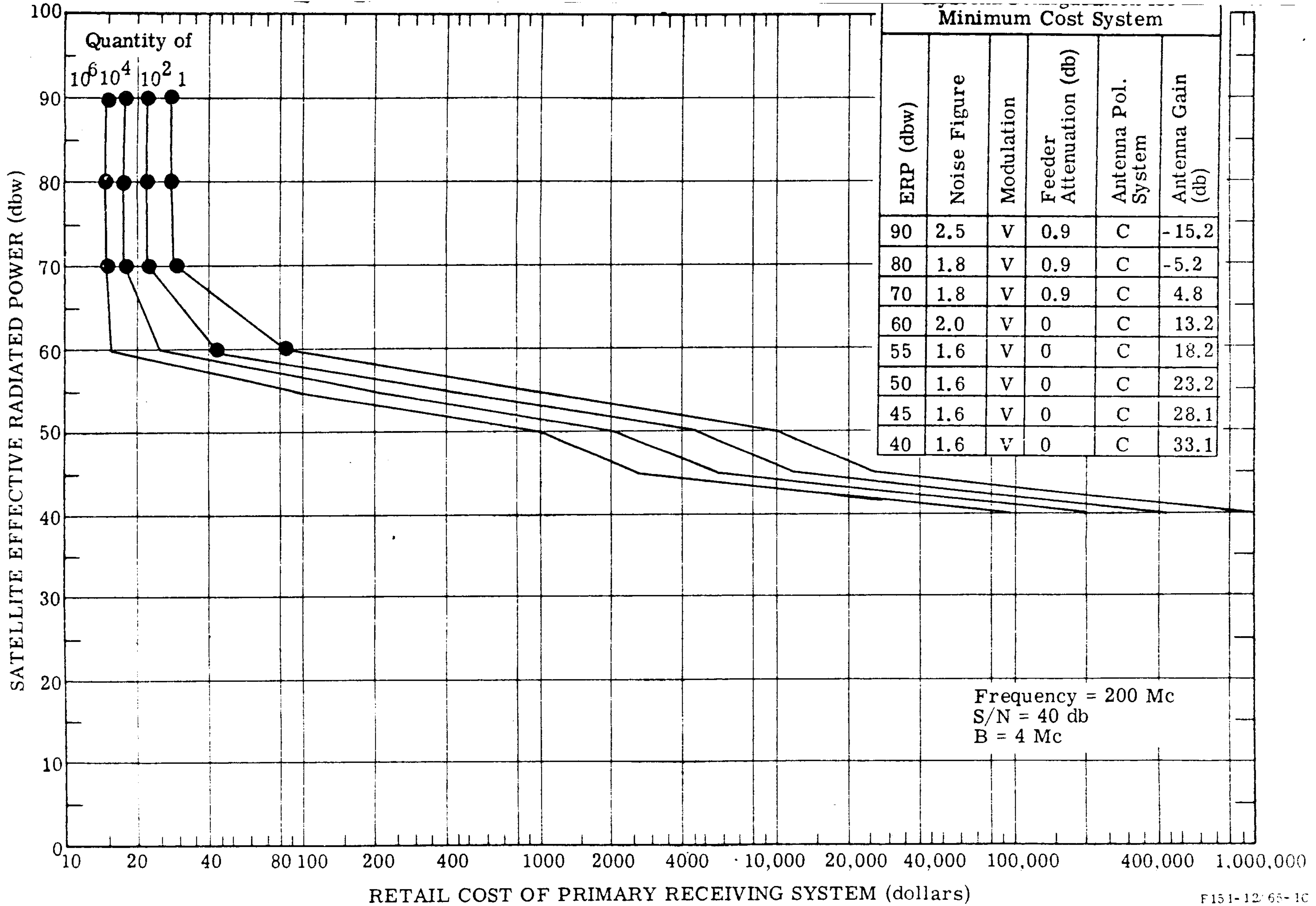
The cost functions for the microwave frequencies are all of the same shape. The cost of a system for 6 Gc/s is about 17 per cent higher than the cost of a 4 Gc/s system requires the same ERP. This percentage difference is independent of ERP. The cost of receiver component at 8 Gc/s is about 50 per cent higher than the cost at 6 Gc/s for ERP's above 50 dbw and about 20 per cent higher at ERP's below 50 dbw. The cost of a 10 Gc/s system is 20 per cent higher than an 8 Gc/s system, and the cost of a 12 Gc/s system is about 20 per cent higher than a 10 Gc/s system.

This increase in cost with frequency is due mainly to the higher amplifier, local oscillator and antenna costs at the higher frequencies.

Comparison of Frequencies

Figure 4.4.17 shows a superposition of the results for a quantity of one at all frequencies, for the maximum noise case. It is interesting to note from this comparison that the optimum frequency depends on ERP. At 90 dbw 200 Mc/s is the optimum frequency. At 70 and 80 dbw 800 Mc/s is the optimum frequency and at 60 dbw, 600 Mc/s, 800 Mc/s, and 1 Gc/s are equally advantageous. From 45 dbw to 55 dbw 1.0 Gc/s is the optimum, and below 45 dbw 2 Gc/s is the optimum frequency.

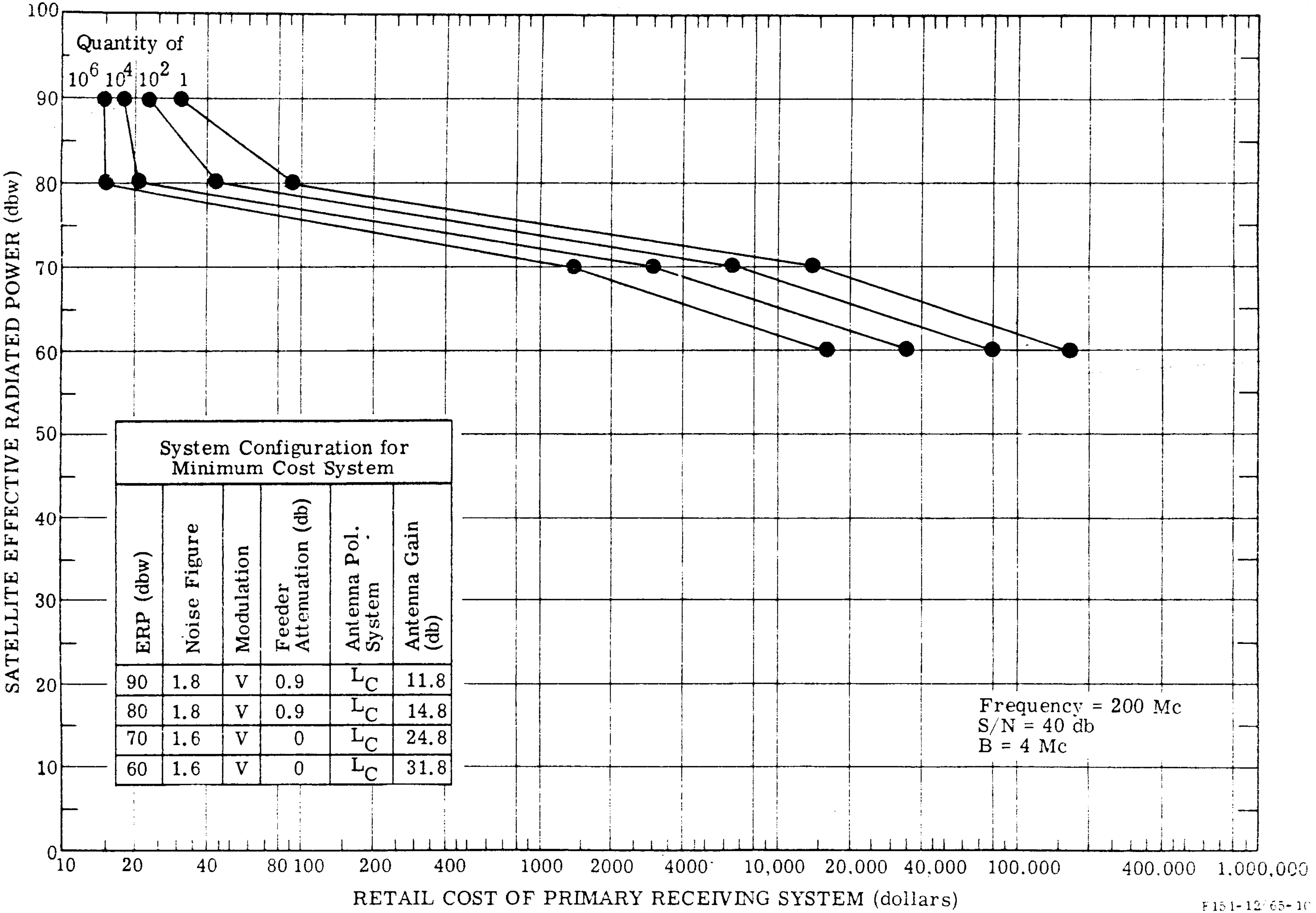
Figure 4.4.18 shows a comparison of the results for varied combinations of minimum cost systems operating at 1.0 Gc/s. A similar curve was included in Section 1 for 600 Gc/s. This figure shows the wide spread in cost resulting from a difference in demand between one and one million. It also shows the importance of using FM for satellite powers of 70 dbw or less. The effect of indigenous noise is shown to



Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	2.5	V	0.9	C	-15.2
80	1.8	V	0.9	C	-5.2
70	1.8	V	0.9	C	4.8
60	2.0	V	0	C	13.2
55	1.6	V	0	C	18.2
50	1.6	V	0	C	23.2
45	1.6	V	0	C	28.1
40	1.6	V	0	C	33.1

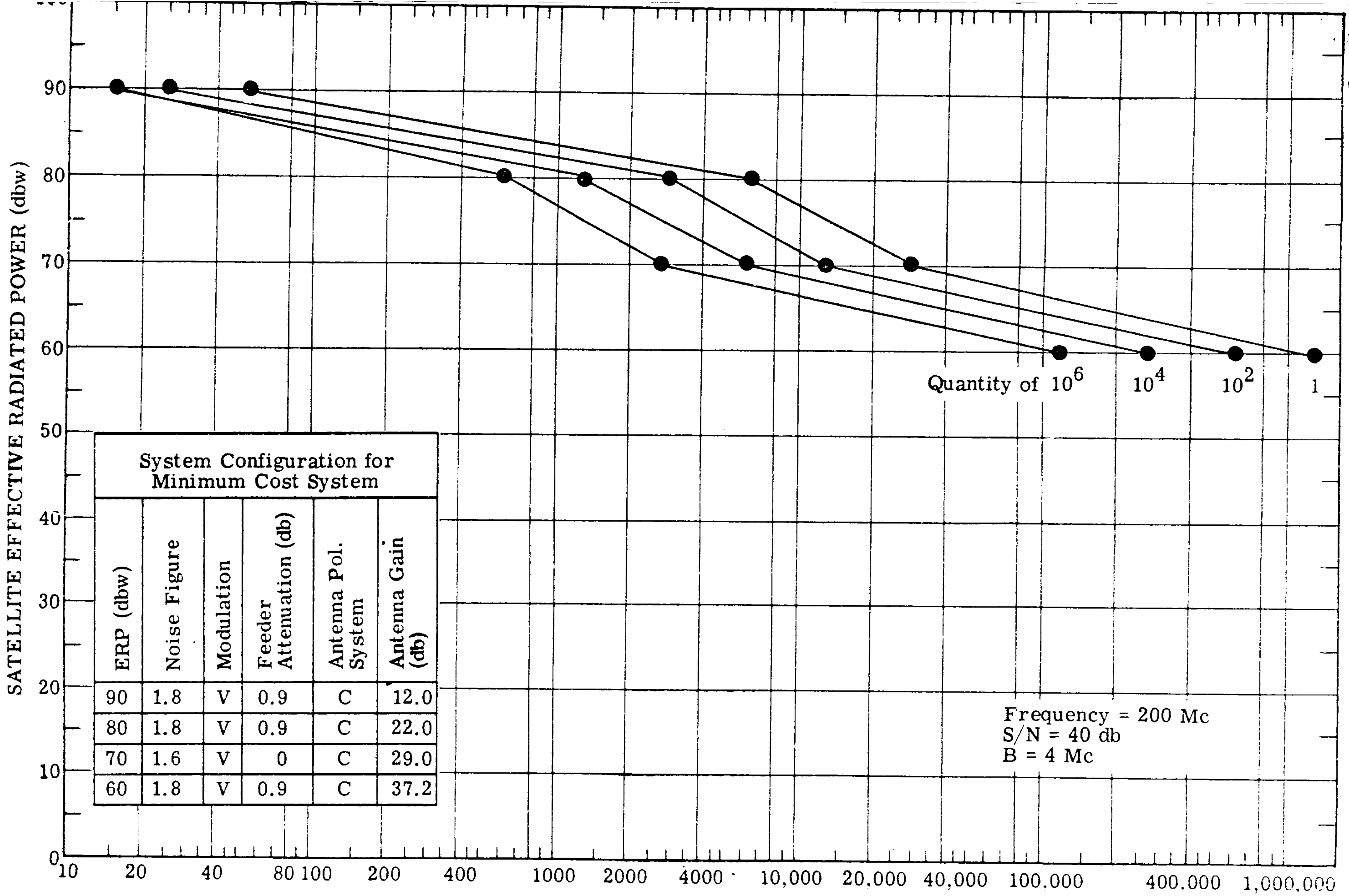
Figure 4.4.1. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 200 Mc, No Indigenous Noise.



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	1.8	V	0.9	L_C	11.8
80	1.8	V	0.9	L_C	14.8
70	1.6	V	0	L_C	24.8
60	1.6	V	0	L_C	31.8

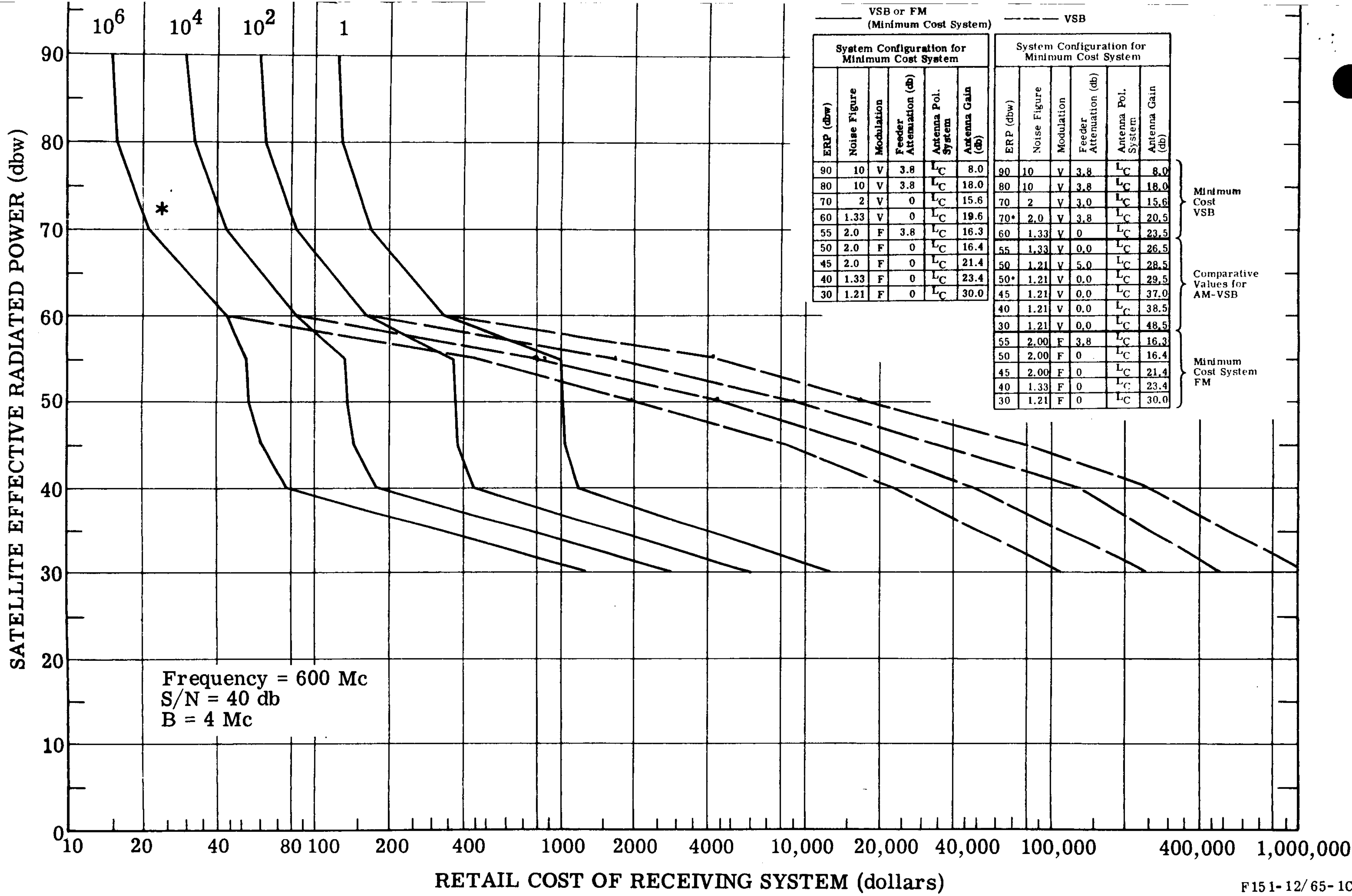
Figure 4.4.2. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 200 Mc, 10 db Below Maximum Indigenous Noise.



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	1.8	V	0.9	C	12.0
80	1.8	V	0.9	C	22.0
70	1.6	V	0	C	29.0
60	1.8	V	0.9	C	37.2

Figure 4.4.3. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 200 Mc, Maximum Indigenous Noise.



VSB or FM (Minimum Cost System)

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	10	V	3.8	L_C	8.0
80	10	V	3.8	L_C	18.0
70	2	V	0	L_C	15.6
60	1.33	V	0	L_C	19.6
55	2.0	F	3.8	L_C	16.3
50	2.0	F	0	L_C	16.4
45	2.0	F	0	L_C	21.4
40	1.33	F	0	L_C	23.4
30	1.21	F	0	L_C	30.0

VSB

	ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
Minimum Cost VSB	90	10	V	3.8	L_C	8.0
	80	10	V	3.8	L_C	18.0
	70	2	V	3.0	L_C	15.6
	70*	2.0	V	3.8	L_C	20.5
	60	1.33	V	0	L_C	23.5
Comparative Values for AM-VSB	55	1.33	V	0.0	L_C	26.5
	50	1.21	V	5.0	L_C	28.5
	50*	1.21	V	0.0	L_C	29.5
	45	1.21	V	0.0	L_C	37.0
	40	1.21	V	0.0	L_C	38.5
	30	1.21	V	0.0	L_C	48.5
Minimum Cost System FM	55	2.00	F	3.8	L_C	16.3
	50	2.00	F	0	L_C	16.4
	45	2.00	F	0	L_C	21.4
	40	1.33	F	0	L_C	23.4
	30	1.21	F	0	L_C	30.0

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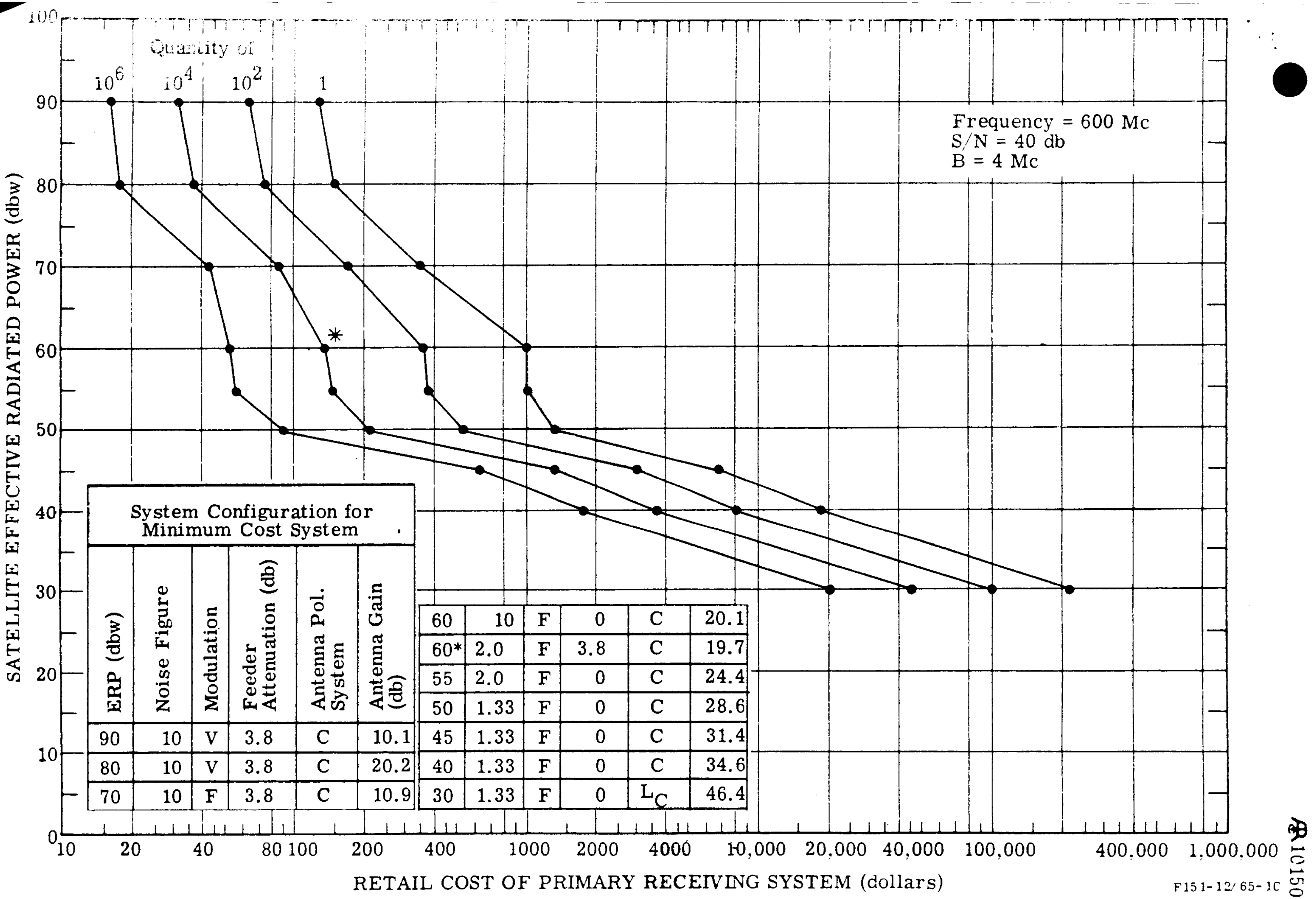
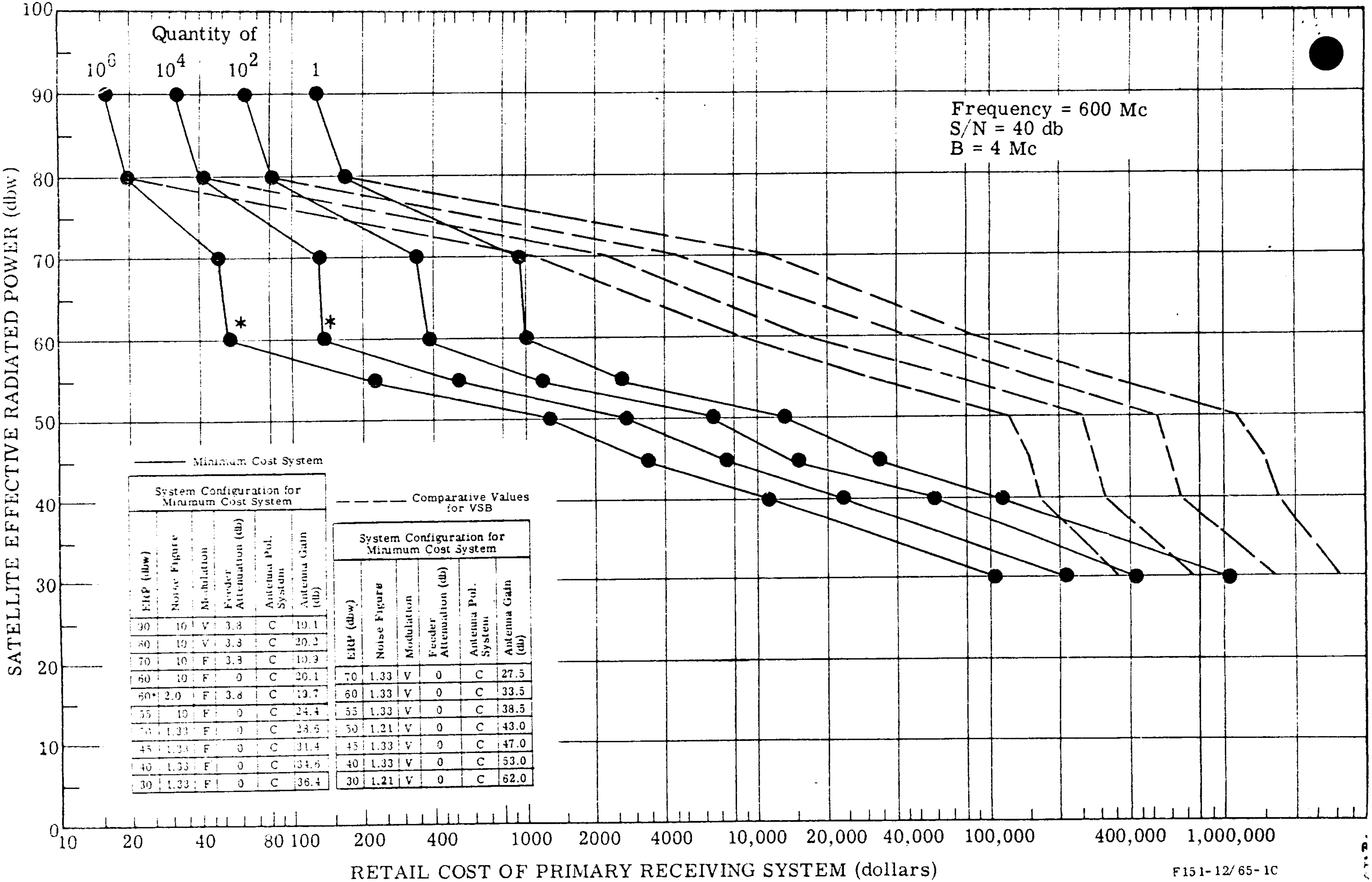
Figure 4.4.4. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 600 Mc, No Indigenous Noise.



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	10	V	3.8	C	10.1
80	10	V	3.8	C	20.2
70	10	F	3.8	C	10.9
60	10	F	0	C	20.1
60*	2.0	F	3.8	C	19.7
55	2.0	F	0	C	24.4
50	1.33	F	0	C	28.6
45	1.33	F	0	C	31.4
40	1.33	F	0	C	34.6
30	1.33	F	0	L_C	46.4

Figure 4.4.5. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 600 Mc, 10 db Below Maximum.



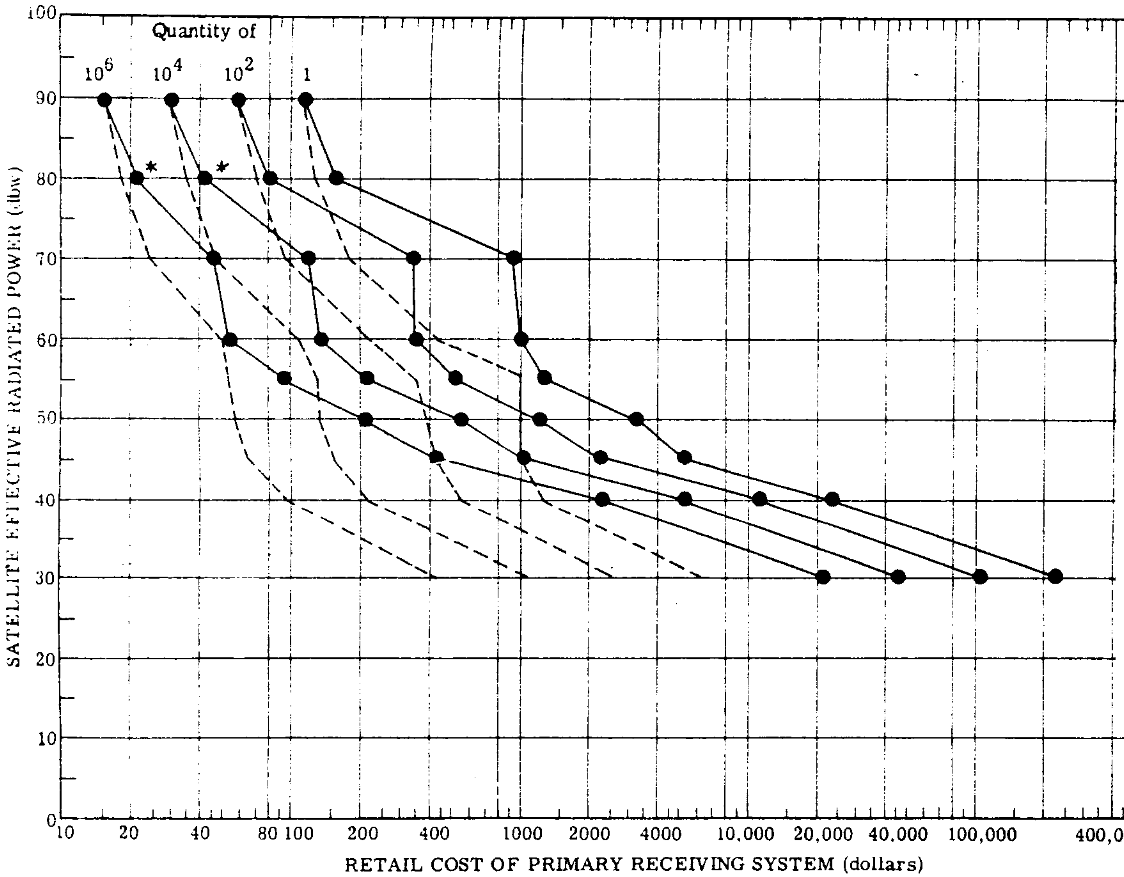
System Configuration for Minimum Cost System (Minimum Cost System)

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	10	V	3.3	C	10.1
80	10	V	3.3	C	20.2
70	10	F	3.3	C	10.9
60	10	F	0	C	20.1
60*	2.0	F	3.6	C	19.7
55	10	F	0	C	24.4
50	1.33	F	0	C	28.5
45	1.33	F	0	C	31.4
40	1.33	F	0	C	34.6
30	1.33	F	0	C	36.4

System Configuration for Minimum Cost System (Comparative Values for VSB)

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
70	1.33	V	0	C	27.5
60	1.33	V	0	C	33.5
55	1.33	V	0	C	38.5
50	1.21	V	0	C	43.0
45	1.33	V	0	C	47.0
40	1.33	V	0	C	53.0
30	1.21	V	0	C	62.0

Figure 4.4.6. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 600 Mc, Maximum Indigenous Noise.



—— Maximum Indigenous Noise

System Configuration for Minimum Cost System					
ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	10	V	5.0	C	11.3
80	10	V	0.9	C	19.5
80*	2.0	V	5.0	C	18.7
70	10	F	5.0	C	12.0
60	10	F	0	C	20.0
55	2.0	F	0	C	23.8
50	2.0	T	0	C	25.7
45	1.33	T	0	C	28.4
40	1.33	T	0	C	33.4
30	1.21	T	0	C	40.4

— — — No Indigenous Noise

System Configuration for Minimum Cost System					
ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	10	V	5.0	C	8.7
80	10	V	5.0	C	18.7
70	2.0	V	5.0	C	17.3
60	1.33	V	0	C	22.0
55	2.0	F	5.0	C	17.0
50	2.0	F	5.0	C	17.1
45	2.0	F	0	C	20.8
40	1.33	F	0	C	22.8
30	1.33	T	0	C	28.9

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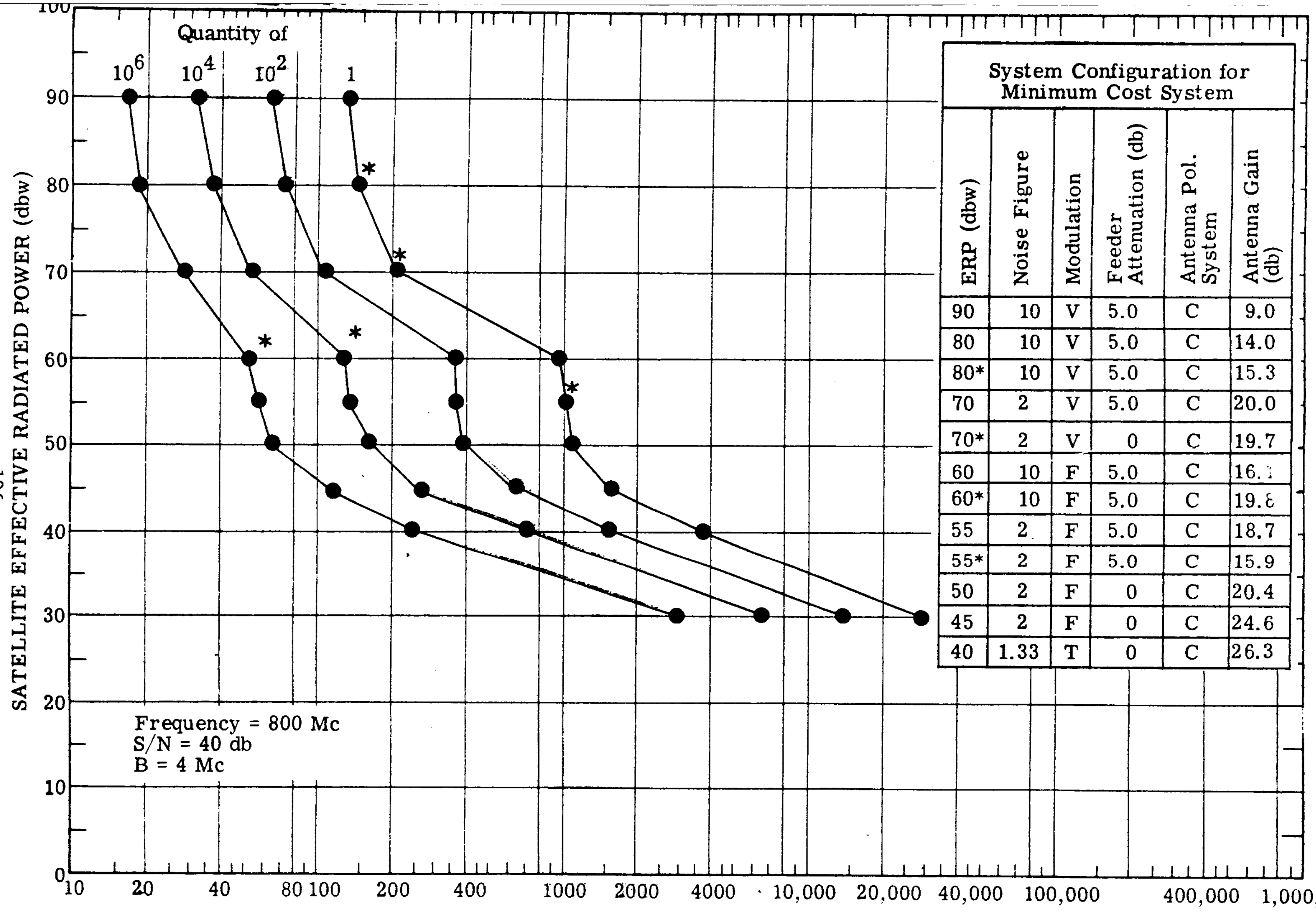
Figure 4.4.7. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 800 Mc, No Indigenous Noise and Maximum Indigenous Noise.

R7964



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	10	V	5.0	C	9.0
80	10	V	5.0	C	14.0
80*	10	V	5.0	C	15.3
70	2	V	5.0	C	20.0
70*	2	V	0	C	19.7
60	10	F	5.0	C	16.[illegible]
60*	10	F	5.0	C	19.8
55	2	F	5.0	C	18.7
55*	2	F	5.0	C	15.9
50	2	F	0	C	20.4
45	2	F	0	C	24.6
40	1.33	T	0	C	26.3

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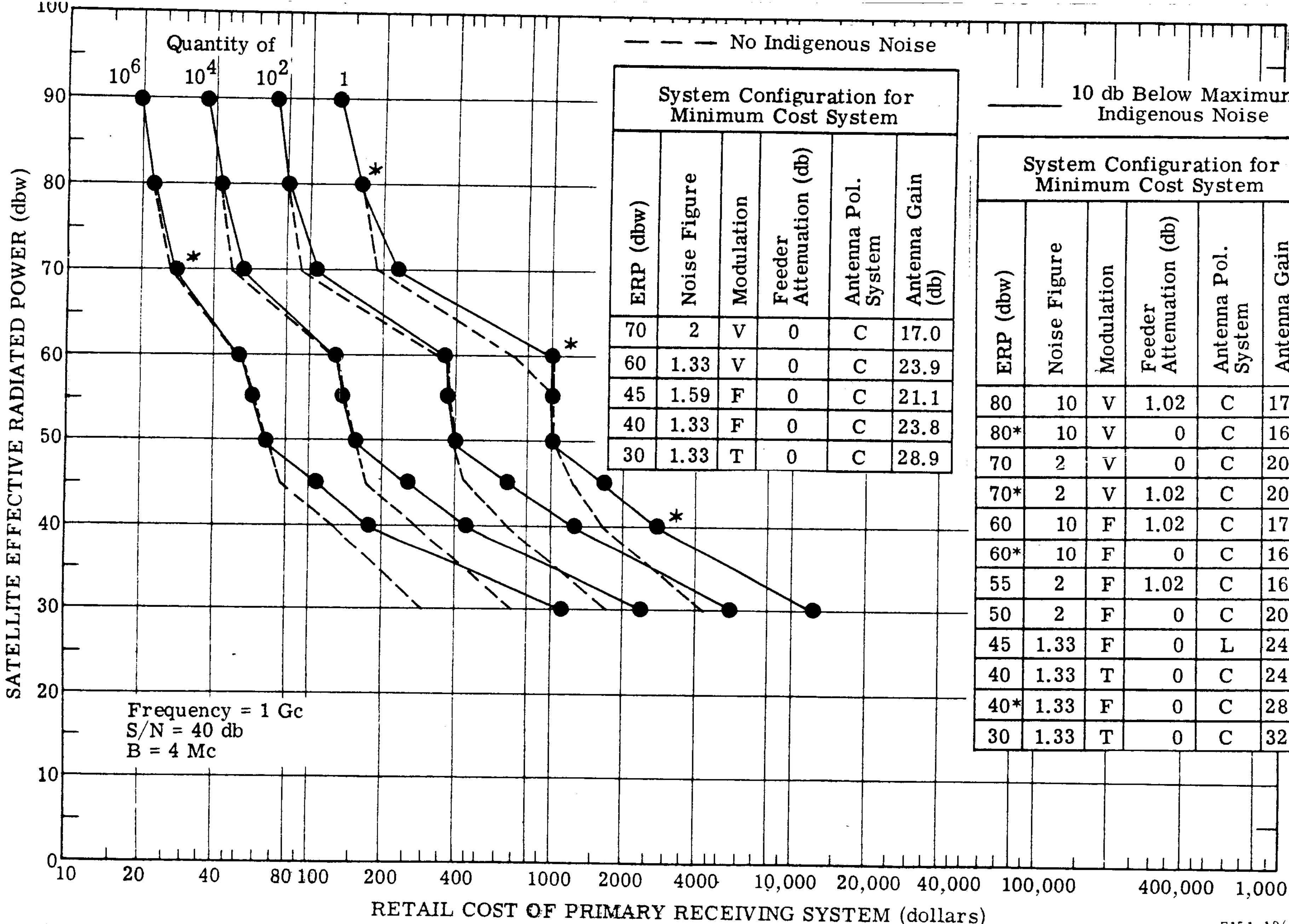
Figure 4.4.8. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 800 Mc, 10 db Below Maximum Indigenous Noise.



No Indigenous Noise — System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
70	2	V	0	C	17.0
60	1.33	V	0	C	23.9
45	1.59	F	0	C	21.1
40	1.33	F	0	C	23.8
30	1.33	T	0	C	28.9

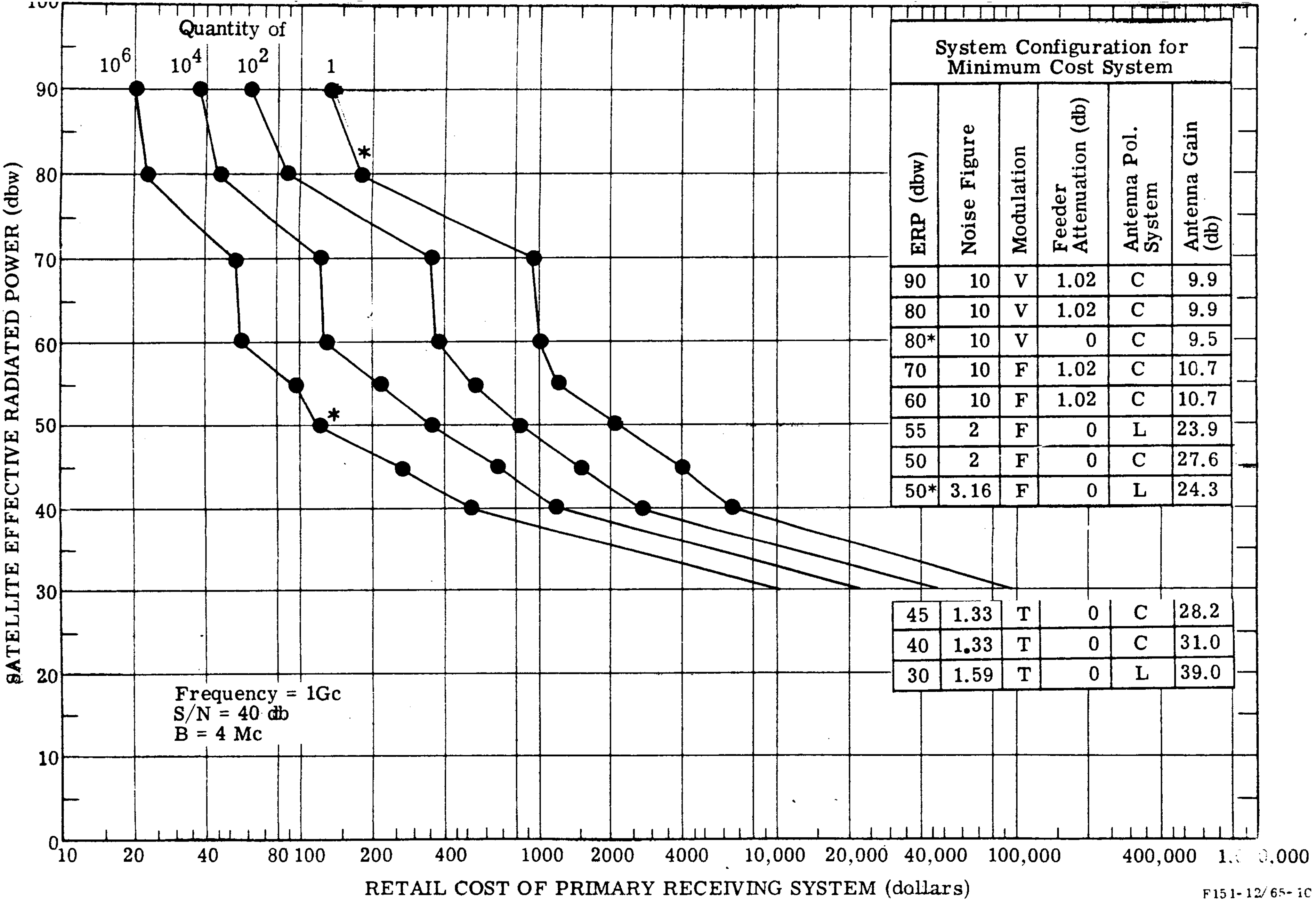
10 db Below Maximum Indigenous Noise — System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
80	10	V	1.02	C	17.1
80*	10	V	0	C	16.1
70	2	V	0	C	20.0
70*	2	V	1.02	C	20.8
60	10	F	1.02	C	17.8
60*	10	F	0	C	16.9
55	2	F	1.02	C	16.7
50	2	F	0	C	20.8
45	1.33	F	0	L	24.2
40	1.33	T	0	C	24.5
40*	1.33	F	0	C	28.6
30	1.33	T	0	C	32.8

F151-12/65-1C

Figure 4.4.9. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 1.0 Gc, No Indigenous Noise and 10 db Below Maximum Indigenous Noise.

R7963



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	10	V	1.02	C	9.9
80	10	V	1.02	C	9.9
80*	10	V	0	C	9.5
70	10	F	1.02	C	10.7
60	10	F	1.02	C	10.7
55	2	F	0	L	23.9
50	2	F	0	C	27.6
50*	3.16	F	0	L	24.3
45	1.33	T	0	C	28.2
40	1.33	T	0	C	31.0
30	1.59	T	0	L	39.0

Figure 4.4.10. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 1.0 Gc, Maximum Indigenous Noise.

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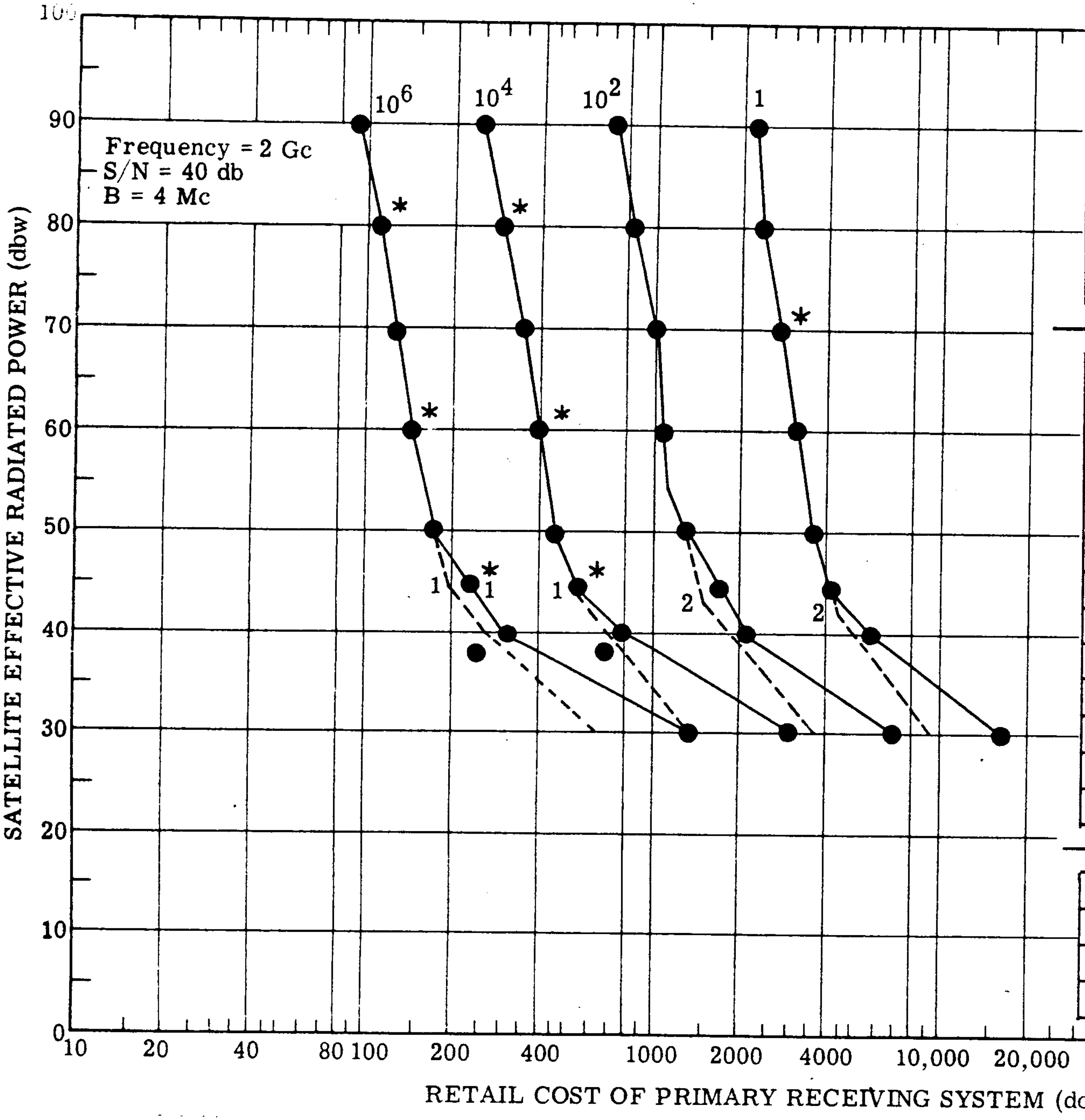

System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
——— Maximum Indigenous Noise					
90	20	V	1.4	L	16.6
80	20	V	1.4	L	26.5
80*	6.31	V	1.4	L	22.0
70	20	F	1.4	L	17.4
70*	6.31	F	1.4	L	30.0
60	20	F	1.4	L	27.2
60*	6.31	F	1.4	L	22.8
55	2.51	F	1.4	L	24.6
50	2.51	F	1.4	L	29.2
45	2.51	F	0	L	32.0
45*	2.51	F	1.4	L	33.4
40	2.51	T	0	L	32.8
30	1.66	T	0	L	39.4
– – – No Indigenous Noise					
45[1]	2.51	F	0	L	29.8
45[2]	2.51	F	1.4	L	31.8
40	2.51	F	0	L	34.6
30	1.66	T	0	L	36.9

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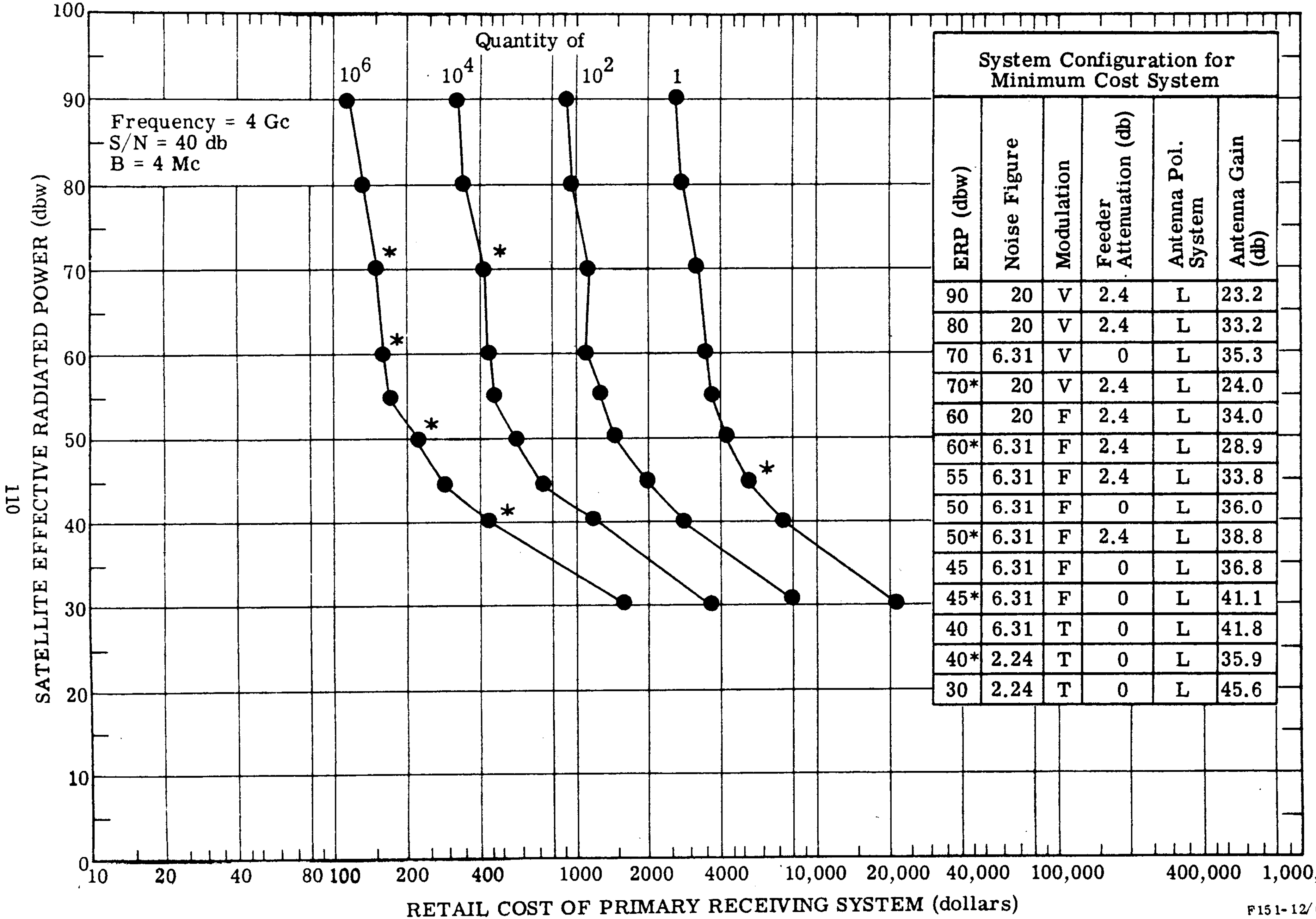
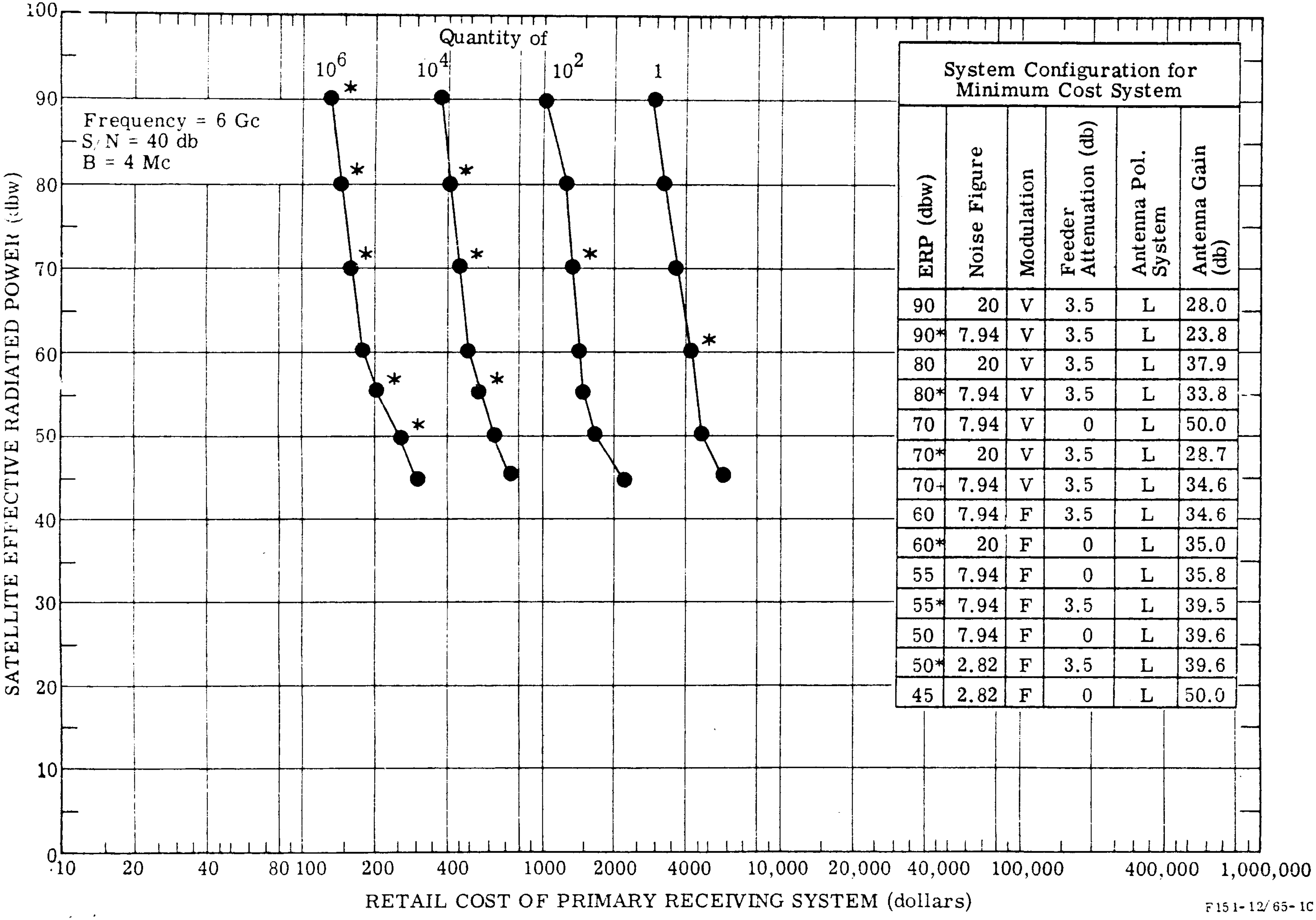
Figure 4.4.11. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 2.0 Gc, No Indigenous Noise and Maximum Indigenous Noise.



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	20	V	2.4	L	23.2
80	20	V	2.4	L	33.2
70	6.31	V	0	L	35.3
70*	20	V	2.4	L	24.0
60	20	F	2.4	L	34.0
60*	6.31	F	2.4	L	28.9
55	6.31	F	2.4	L	33.8
50	6.31	F	0	L	36.0
50*	6.31	F	2.4	L	38.8
45	6.31	F	0	L	36.8
45*	6.31	F	0	L	41.1
40	6.31	T	0	L	41.8
40*	2.24	T	0	L	35.9
30	2.24	T	0	L	45.6

Figure 4.4.12. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 4.0 Gc.



System Configuration for Minimum Cost System					
ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	20	V	3.5	L	28.0
90*	7.94	V	3.5	L	23.8
80	20	V	3.5	L	37.9
80*	7.94	V	3.5	L	33.8
70	7.94	V	0	L	50.0
70*	20	V	3.5	L	28.7
70+	7.94	V	3.5	L	34.6
60	7.94	F	3.5	L	34.6
60*	20	F	0	L	35.0
55	7.94	F	0	L	35.8
55*	7.94	F	3.5	L	39.5
50	7.94	F	0	L	39.6
50*	2.82	F	3.5	L	39.6
45	2.82	F	0	L	50.0

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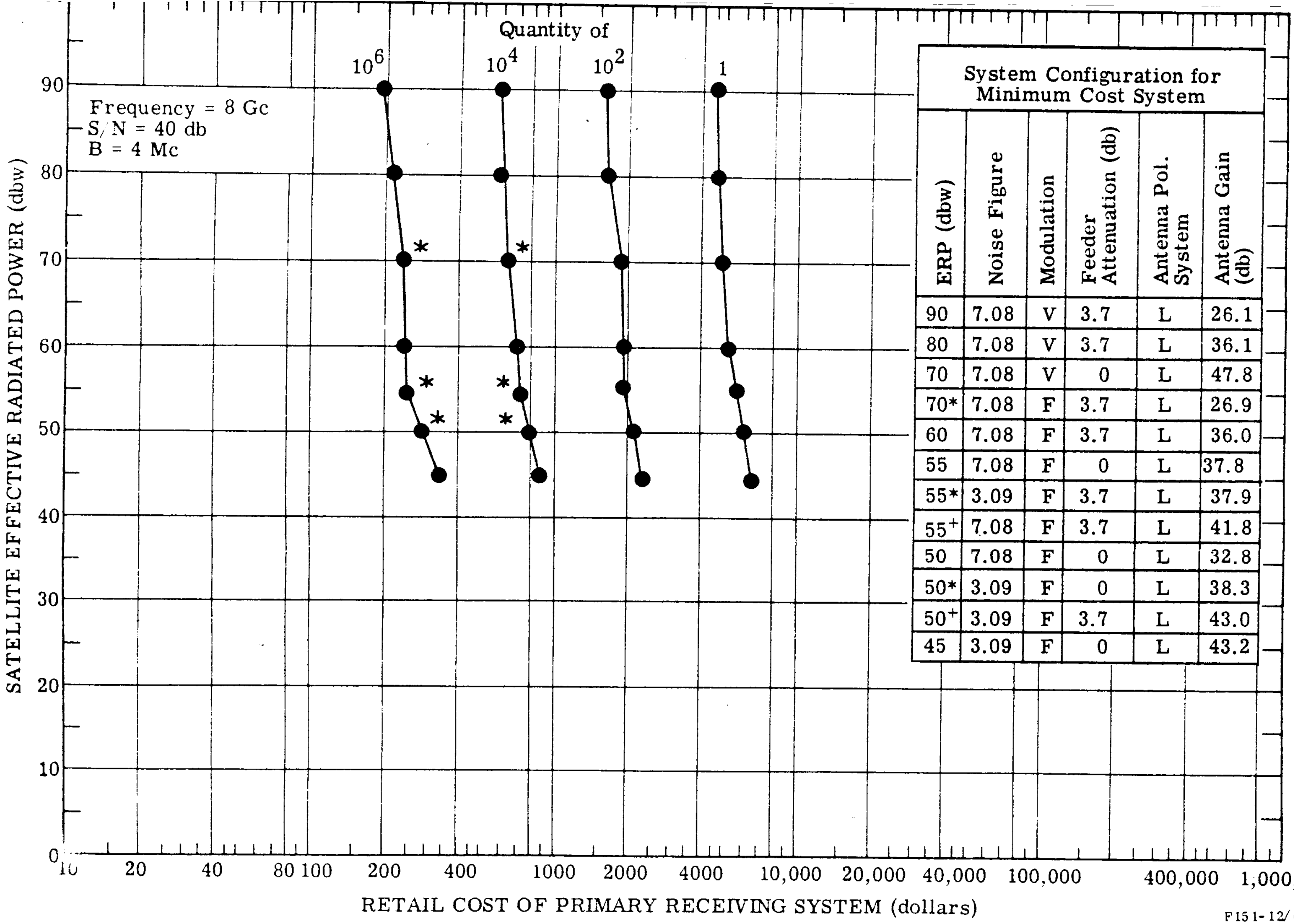
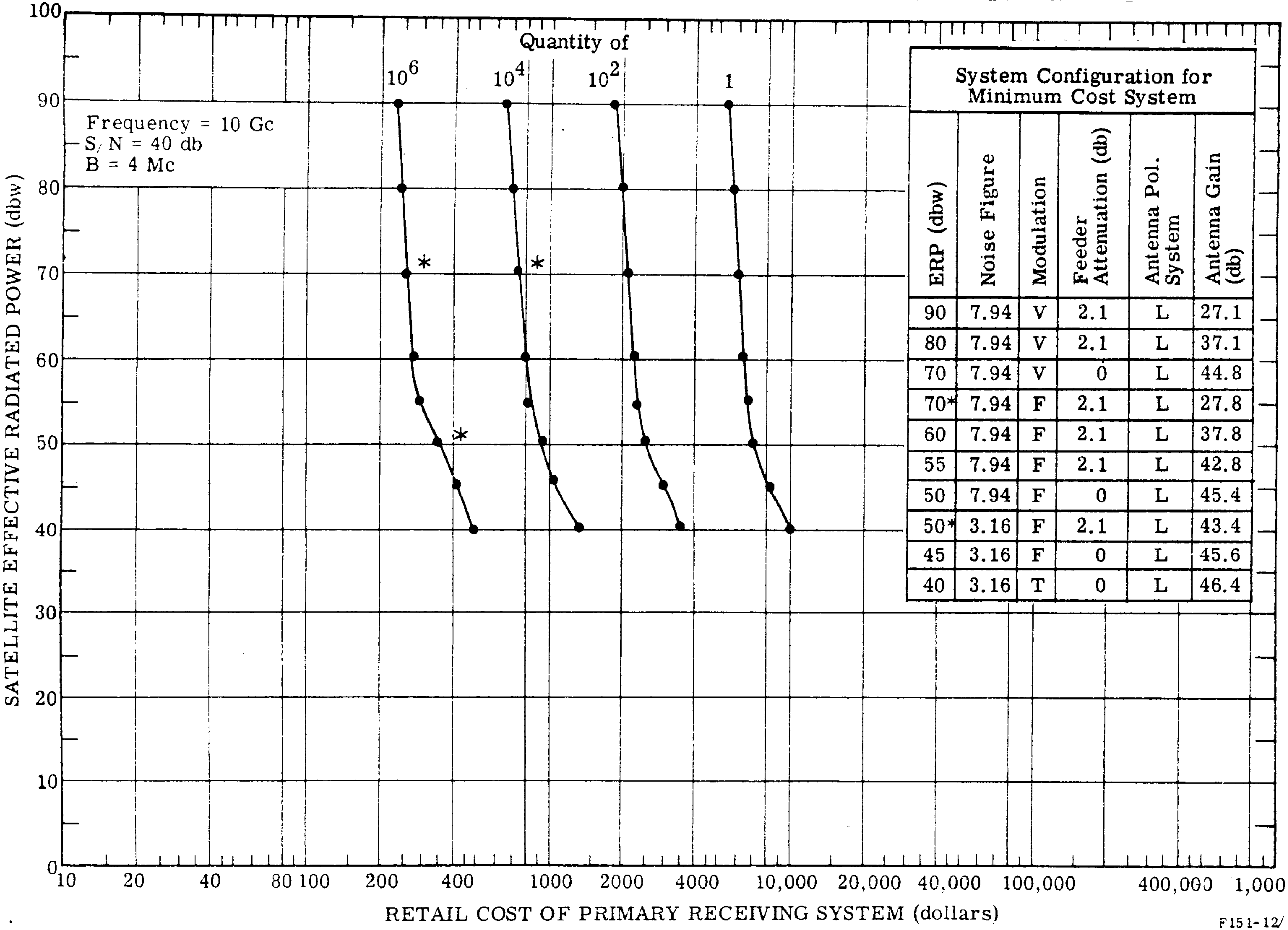
Figure 4.4.13. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 6.0 Gc.



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	7.08	V	3.7	L	26.1
80	7.08	V	3.7	L	36.1
70	7.08	V	0	L	47.8
70*	7.08	F	3.7	L	26.9
60	7.08	F	3.7	L	36.0
55	7.08	F	0	L	37.8
55*	3.09	F	3.7	L	37.9
55^+	7.08	F	3.7	L	41.8
50	7.08	F	0	L	32.8
50*	3.09	F	0	L	38.3
50^+	3.09	F	3.7	L	43.0
45	3.09	F	0	L	43.2

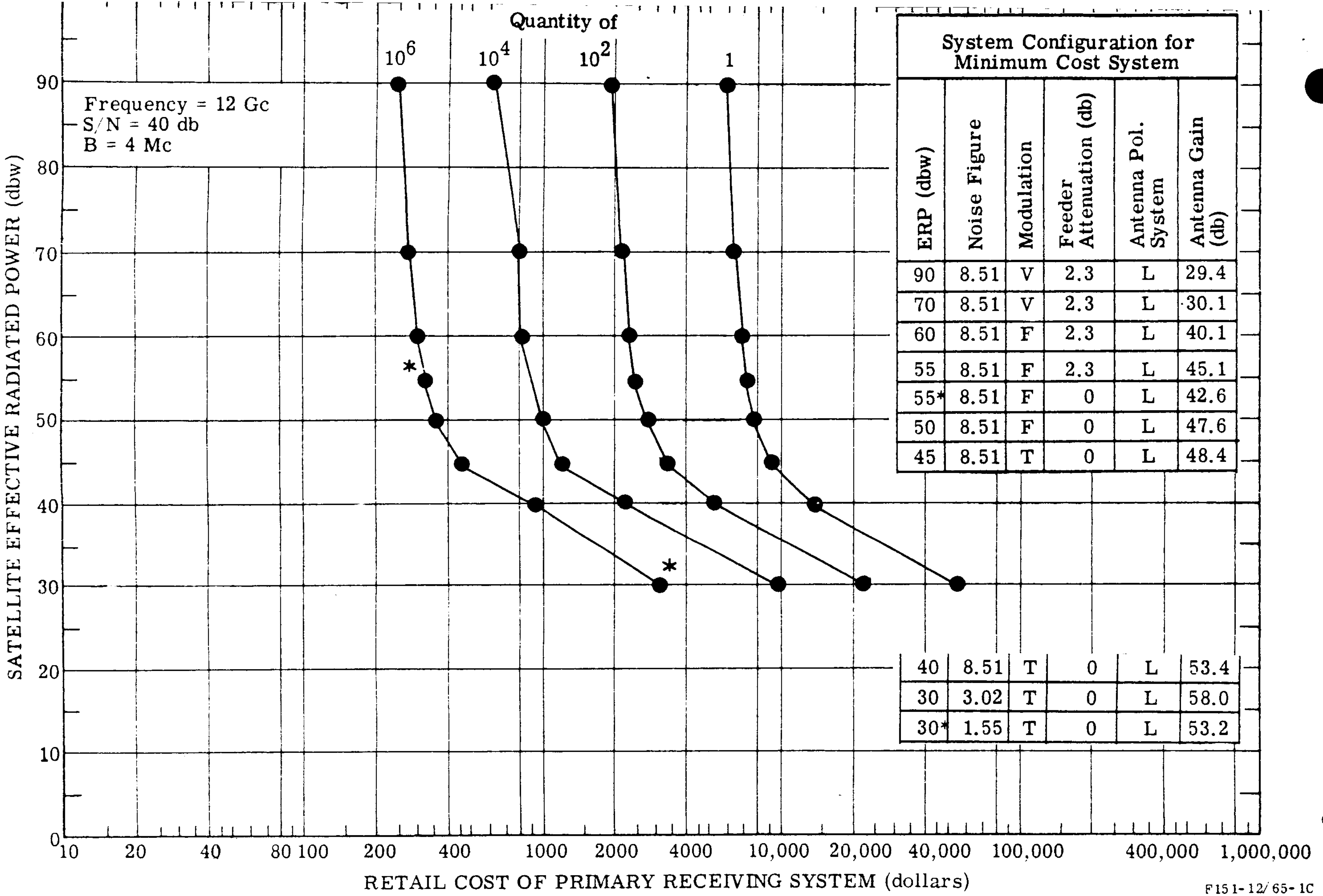
Figure 4.4.14. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 8.0 Gc.



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	7.94	V	2.1	L	27.1
80	7.94	V	2.1	L	37.1
70	7.94	V	0	L	44.8
70*	7.94	F	2.1	L	27.8
60	7.94	F	2.1	L	37.8
55	7.94	F	2.1	L	42.8
50	7.94	F	0	L	45.4
50*	3.16	F	2.1	L	43.4
45	3.16	F	0	L	45.6
40	3.16	T	0	L	46.4

Figure 4.4.15. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 10 Gc.



System Configuration for Minimum Cost System

ERP (dbw)	Noise Figure	Modulation	Feeder Attenuation (db)	Antenna Pol. System	Antenna Gain (db)
90	8.51	V	2.3	L	29.4
70	8.51	V	2.3	L	30.1
60	8.51	F	2.3	L	40.1
55	8.51	F	2.3	L	45.1
55*	8.51	F	0	L	42.6
50	8.51	F	0	L	47.6
45	8.51	T	0	L	48.4
40	8.51	T	0	L	53.4
30	3.02	T	0	L	58.0
30*	1.55	T	0	L	53.2

Figure 4.4.16. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 12 Gc.

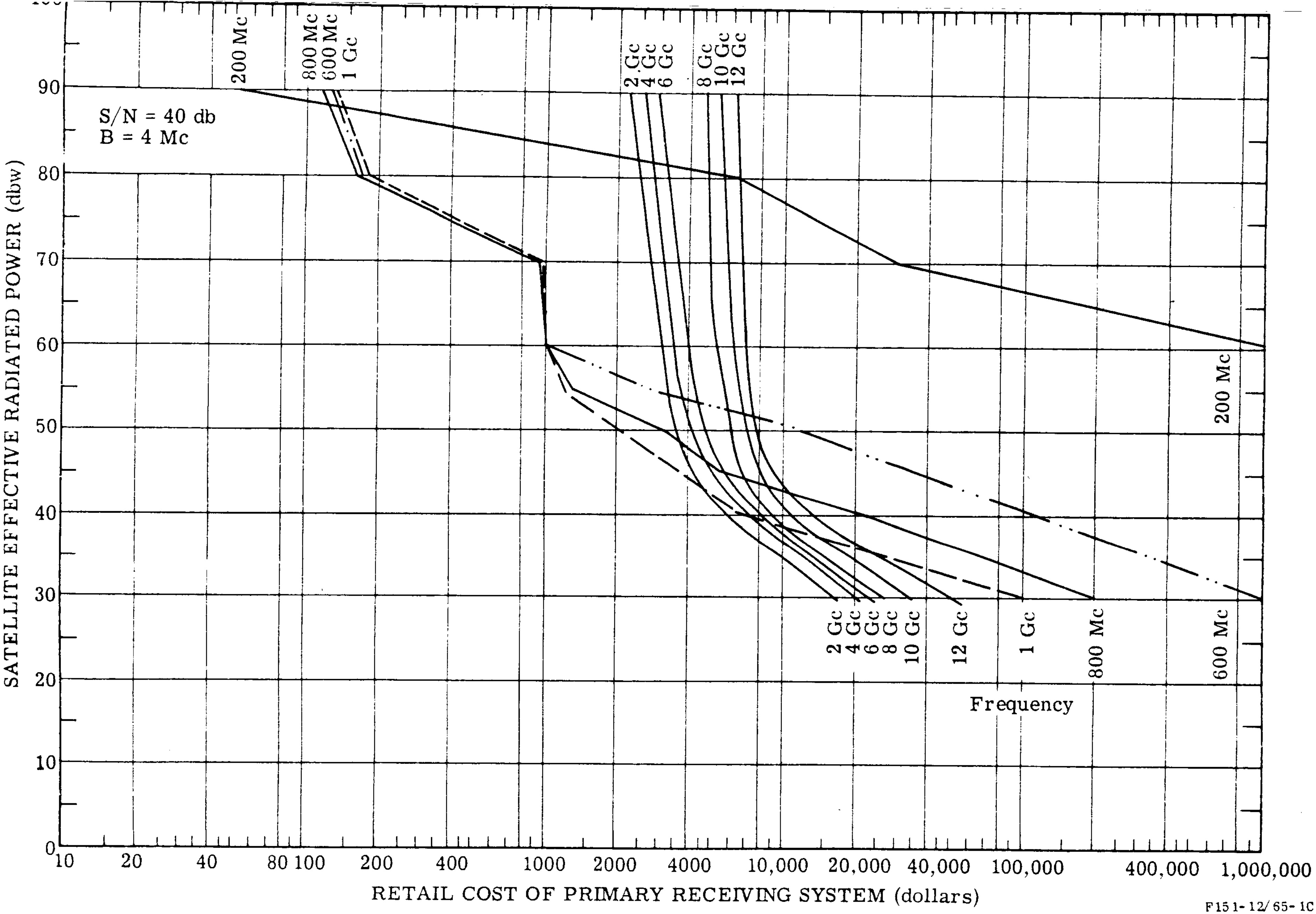


Figure 4.4.17. Retail Cost Versus Required Satellite Power for Minimum Cost Receiving Systems at Various Frequencies, Quantity of 1, Maximum Indigenous Noise.

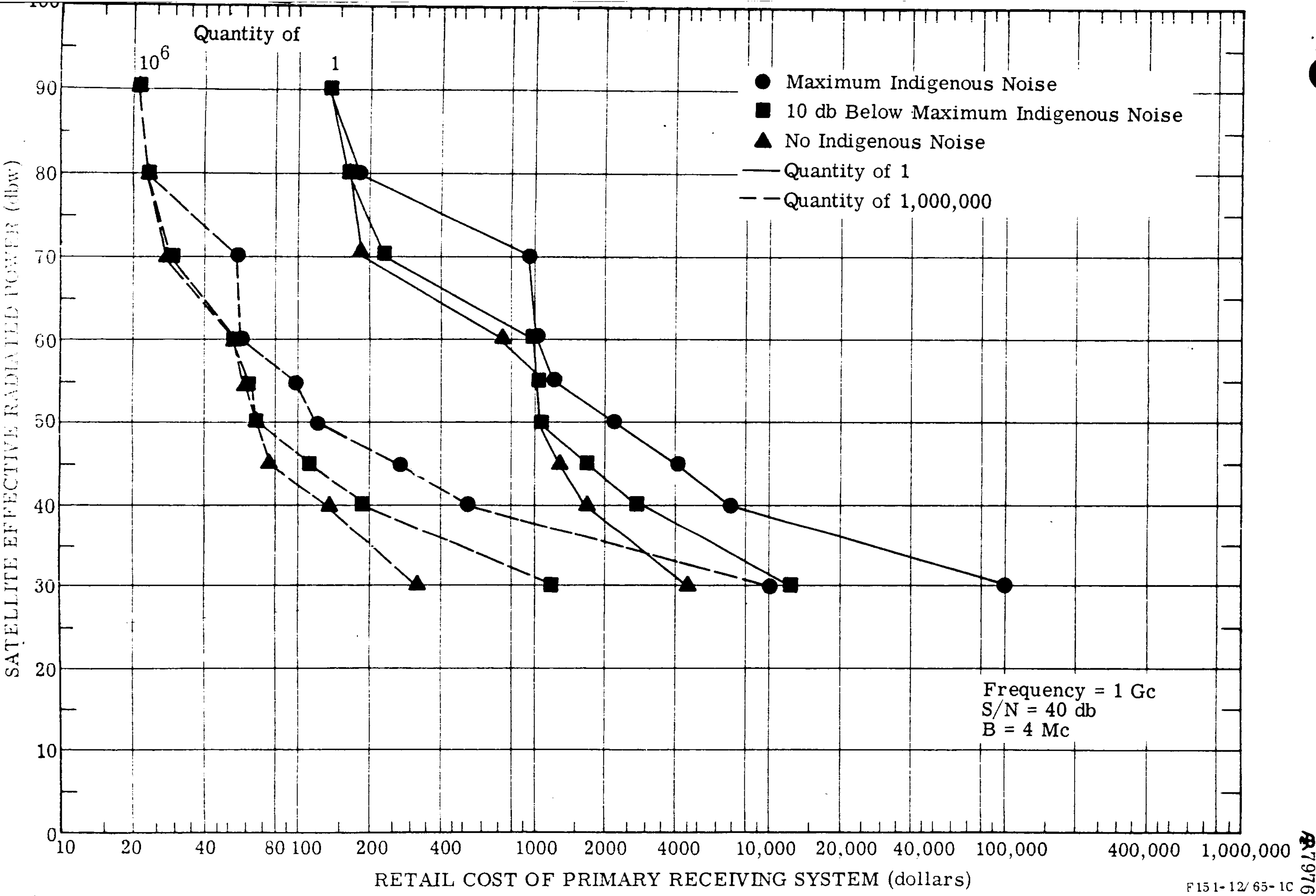


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Figure 4.4.18. Retail Cost Versus Required Satellite Power for Various Quantities of Minimum Cost Receiving Systems at 1 Gc, for Different Values of Indigenous Noise.

be increasingly important as satellite powers of less than 50-60 dbw are used.

It should be emphasized as has already been described in this report that there is a need for better data on indigenous noise and on the effect of the ionosphere in limiting bandwidth. This report has used the best available sources for both types of data. Because the results for operation at 1 G/cs as shown in Figure 4.4.18 show the possibility for reasonably low cost receiver components to operate with satellites having powers as low as 30 dbw. The validity of noise data and the possibility for operation with FM bandwidthes at 1 Gc/s (or less) become extremely important. Above 1 Gc/s both noise and bandwidth limitations are less severe but equipment components become more expensive.

4.5 CORRECTION FACTORS TO THE RECEIVER COST VERSUS SATELLITE ERP CURVES

4.5.1 General

For specific applications of satellite television, different bandwidths and desired output signal-to-noise ratios may be considered. An example of this would be a color television application in which the based video bandwidth would be 6.0 Mc/s instead of 4.0 Mc/s. A second example would be a satellite which is used as a television relay link in which a $(S/N)_o$ of the receiver would be required to be greater than 40 db.

Methods are given below which will enable the interpretation of the receiver cost versus satellite ERP curves for different output signal-to-noise ratios and bandwidths.

4.5.2 Bandwidth Correction Factor Curve

As the system base bandwidth is increased, more noise enters the system. For those types of noise which can be classified as white noise, the noise power at the receiver output increases linearly with the increase in bandwidth. The increase in output noise must be compensated for by the same increase in ERP. For those cases in which the noise is predominantly white the ERP correction factor is given simply as

$$\frac{P_T(BW)}{P_T(4m)} = \frac{BW}{4Mc/s}$$

All noise contributions considered in the system equation are white noise except the indigenous noise contribution.

As shown in Figure 2.5.3, the amount of indigenous noise is not linearly related to bandwidth. Figure 4.5.1 gives the ERP correction to be applied to the results shown for 4Mc/s for those cases where indigenous noise is predominant. This 4 Mc/s correction factor is developed from the 10 Kc/s correction factor shown in Figure 2.5.3.

4.5.3 Output Signal-to-Noise Ratio Correction Factors

Figure 4.5.2 has been prepared to indicate the correction factors that might be applied to obtain relationships between signal-to-noise output of a receiving installation and required satellite ERP for values of signal-to-noise output different from 40 db and for either vestigial sideband reception or FM reception. It is important to recall that the signal-to-noise ratio of 40 db used in this study is the value for excellent picture reception that applies to vestigial sideband reception only. For a value of 40 db at the output VSB provides excellent picture quality. The corresponding signal-to-noise output for equivalent

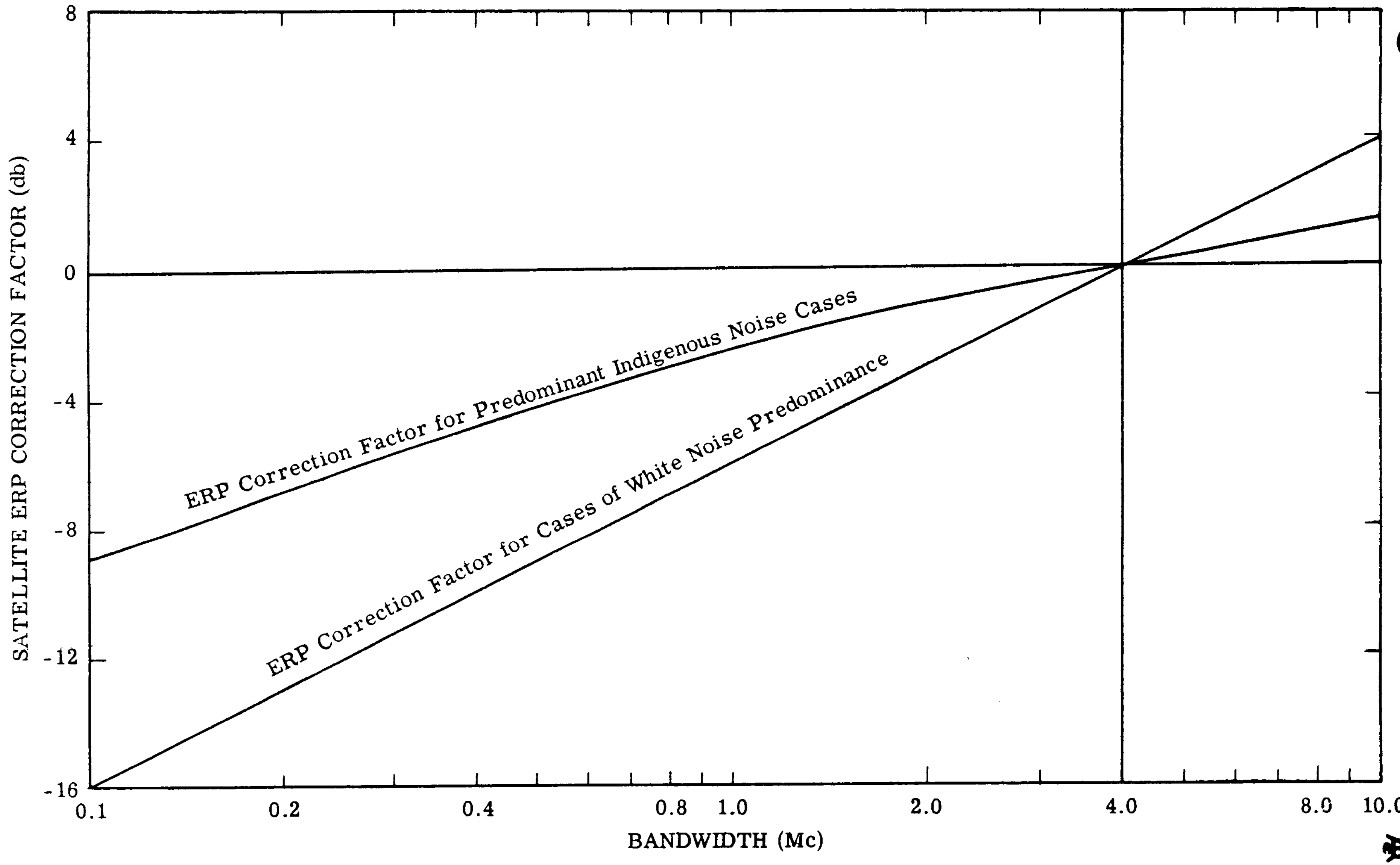

Figure 4.5.1. Satellite ERP Correction Factor to the Receiver Cost Curves for Bandwidths Other Than 4 Mc.

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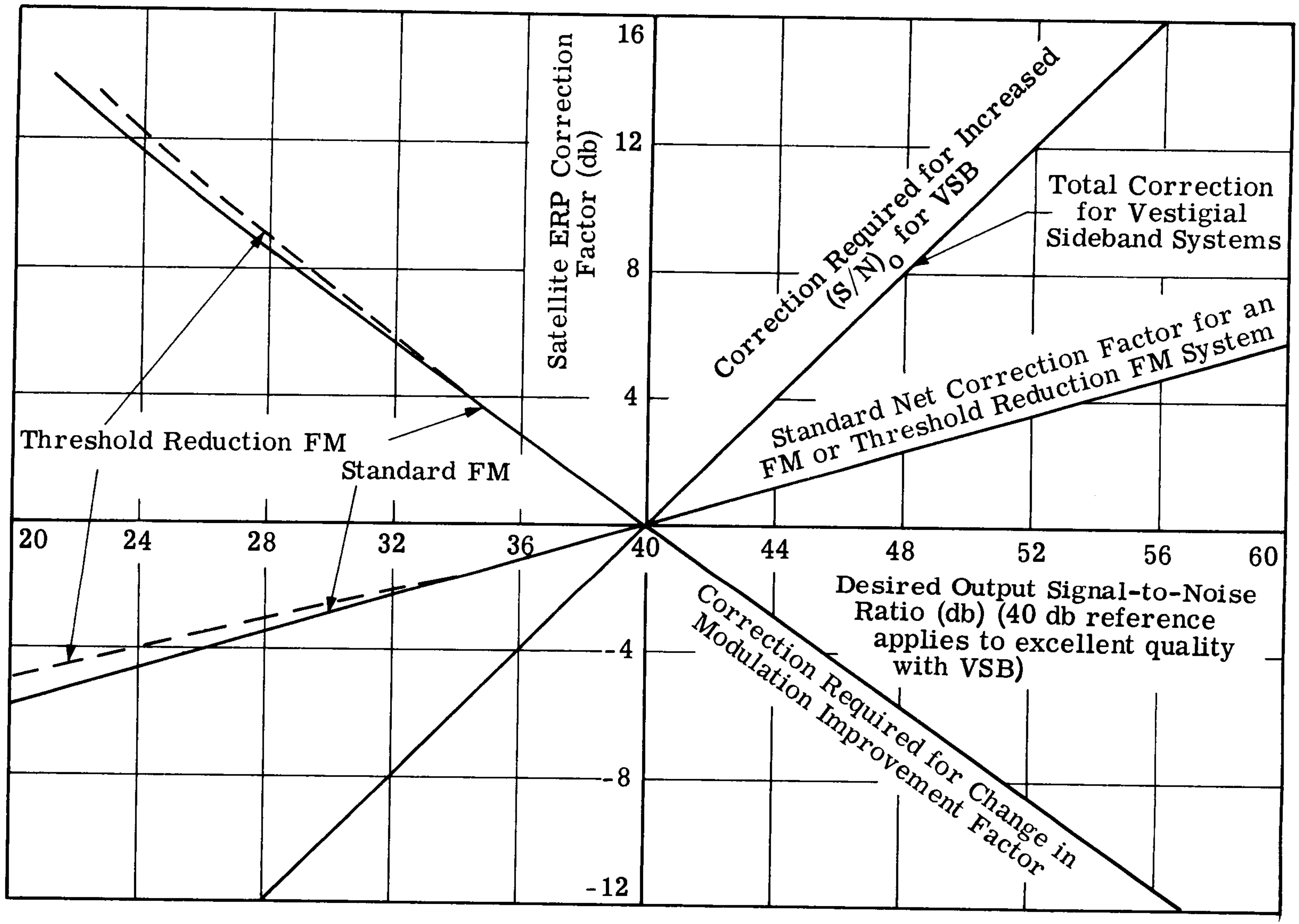

Figure 4.5.2. Satellite ERP Correction Factor to the Receiver Cost Curves for $(S/N)_o$ Other than 40 db.

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quality when FM is 32.3 db. The difference of approximately 8 db is due to the fact that the input noise with FM has different characteristics from that for vestigial sideband. Thus while the correction factors shown in Figure 4.5.2 are shown relative to a 40 db signal-to-noise ratio, it should be kept in mind that to achieve an equivalent quality for FM, the corresponding value is 32.3 db. With this qualification the correction factors shown in Figure 4.5.2 permit the determination of factors to be used in correcting the required satellite ERP for variations of quality with reference to the equivalent of 40 db signal-to-noise output for VSB.

The ERP correction required for changes in output quality $(S/N)_o$ is linear with a slope of 1 for VSB. This is shown in Figure 4.5.2 by the curve marked "correction required for increased $(S/N)_o$ for VSB." For FM the change in required ERP for improvement in quality (Higher $(S/N)_o$) has a slope less than one due to the fact that the required increase in ERP is reduced because with FM a modulation improvement is realized.

By reference to Figure 3.4.3 of Section 3 the modulation improvement of FM can be determined for any derived value of $(S/N)_o$. Thus, if a particular value of improvement or relaxation in desired output signal-to-noise ratio is assumed, then the improvement factor that will be realized with an FM system operating at the threshold can be determined from Figure 3.4.3. The values for the improvement determination in this way are shown in db on the curve in Figure 4.5.2 titled "Correction Required for Change in Modulation Improvement Factor." This curve shows the amount of reduction in required ERP from that which would be required for VSB for a given db change in $(S/N)_o$. For example, for a 4 db increase in desired output signal-to-noise or a quality equivalent to 44 db signal-to-noise with VSB. The improvement factor for FM is 3 db greater than that which is realized for FM having a quality equivalent to that provided with $(S/N)_o$ of 40 db using VSB. Thus, instead of being required to increase the effective radiated power linearly by a factor of 4 db as is the core for VSB with FM it is necessary to increase the effective radiated power by 4 db less approximated 3 db or approximately 1 db. The net correction factor that is required with FM is shown on the curve titled "Standard Net Correction Factor for an FM or Threshold Reduction FM System." This curve is derived by taking the values for ERP that would be required if no modulation improvement exists, such as is the case for vestigial sideband, and subtracting from it the improvement factor realized with FM. This allows a reduction in the required ERP by an amount corresponding to this improvement factor. The sum of the ERP required for no modulation improvement and the effective radiated power correction applicable to an FM improvement which is an effective reduction in required ERP gives the net correction factor applicable to FM systems.

Using the correction factor curves from Figure 4.5.2 it is possible to adjust the required satellite ERP calculated in this report for quality corresponding to a VSB output $(S/N)_o$ of 40 db to obtain required ERP for various other conditions.

Correction for

Final Report

TECHNICAL AND COST FACTORS

THAT AFFECT TELEVISION RECEPTION FROM

A SYNCHRONOUS SATELLITE

Dated: June 30, 1966 TR-PL-9037

Please change Noise Figure of ERP's 90, 80, 70, and 60 on page 109 to each read 2.0.

APPENDIXES

A. ENVIRONMENTAL ATTENUATION AND LOSS FACTORS

B. ENVIRONMENTAL NOISE

C. MODULATION ANALYSIS

D. TELEVISION STANDARDS

APPENDIX A

ENVIRONMENTAL ATTENUATION AND LOSS FACTORS

A-1 GENERAL

The absorption coefficients resulting from rain and atmospheric losses both attenuate the desired signal and the added system noise. For most cases these effects are small and increase with frequency. Since loss due to Faraday rotation is not an absorption loss, it does not add system noise.

A-2 IONOSPHERIC AND ATMOSPHERIC ATTENUATION (α and β)

Although we have considered α and β in the general system equation, they are for the most part quite small over the frequency range 0.1 Gc/s $\leq f \leq$ 12 Gc/s. They are, however, important factors in limiting the frequency range of consideration and at receiving sites with very small elevation angles (large θs).

α, the ionospheric absorption, decreases with frequency and at frequencies above 100 Mc/s makes a system noise contribution[1] of about 10° corresponding to an attenuation of about 0.1 db. Cosmic noise as shown in Figure A-1b at 100 Mc/s is between 500° and 2,000° K. Due to the low value of ionospheric attenuation and the extremely small contribution to effective noise temperature compared with cosmic noise, the effect of ionospheric attenuation α can be neglected for the purpose of this study.

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[1] Bagdady, E. J., ed. Lectures on Communication System Theory. McGraw-Hill, 1961.

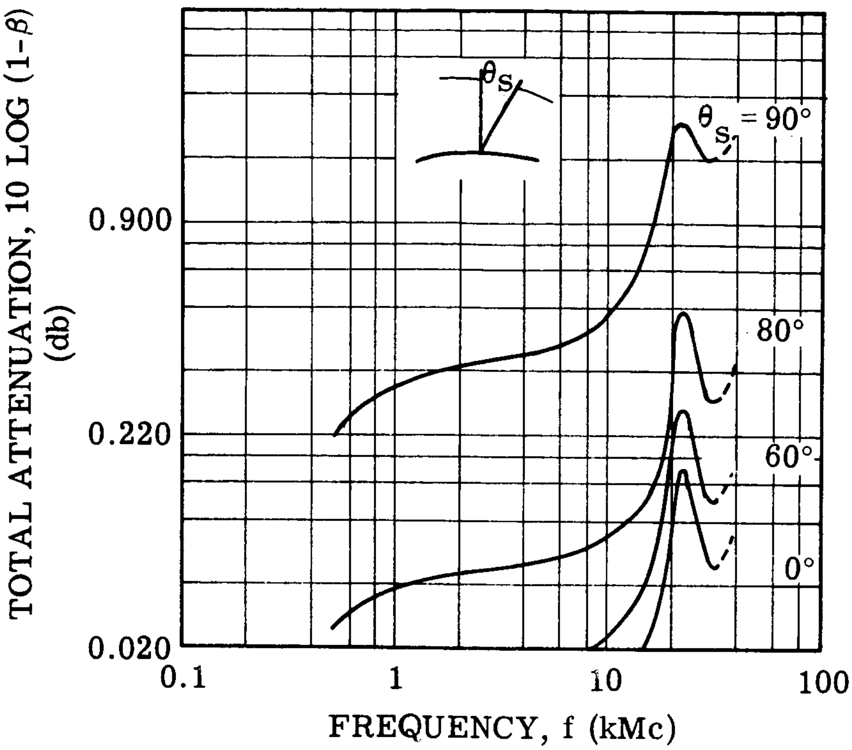

Figure A-1a. One-Way Attenuation Through the Atmosphere Due to Oxygen and Water Vapor (Summer Conditions).

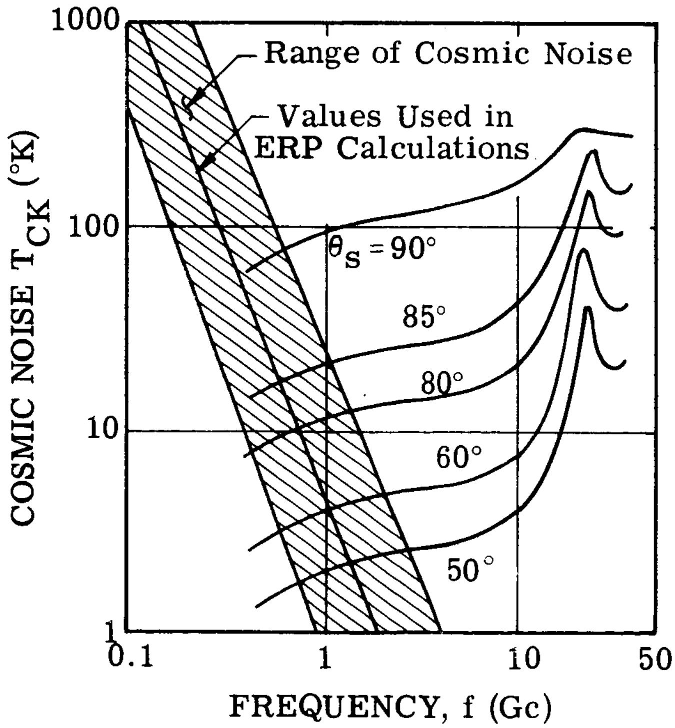

Figure A-1b. β and $\beta\, T_{atm}$ as a Function of θ_s and Frequency.

β, the atmospheric absorption, increases with frequency and effectively establishes the upper limit of the considered frequency range. Atmospheric absorption β is caused mainly by the resonance of water vapor molecules at 50 Gc/s. The tails of these resonance curves determine the value of β below 10 Gc/s. β is an absorption factor expressed as a normalized percentage reference to unity. Attenuation which is a ratio normally expressed in db is related to the value of β by the relationship:

$$\text{Attenuation in db} = 10 \log (1-\beta)$$

where β is absorption expressed as a ratio or normalized percentage. Figure A-1a gives the values of $10 \log (1-\beta)$, which is the actual signal attenuation, as a function of frequency and θs. Figure A-2.4.1b gives the value of atmospheric noise temperature βT_{atm} for the same variables. T_{atm}, the ambient temperature of the atmosphere is considered to be 290° K. As θ increases, the ray path goes through a longer length of atmosphere and as a result, the signal is attenuated more. The curves showing attenuation $\left[10 \log (1-\beta)\right]$ and effective atmospheric noise βT_{atm} are derived from data reported by Hogg and Mumford[1] and Rosenfeld[2], respectively.

For antenna elevation angles greater than 7° above the horizontal, the absorption β has no noticeable diurnal variation, and only a very slight yearly variation. For those cases in which the value of absorption β is not negligible, it will be considered as time invariant.

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[1] Hogg, D. C., and Mumford, W. W., "The Effective Noise Temperature of the Sky." The Microwave Journal, March 1960, p. 80.

[2] Rosenfeld, M. M., "Noise in Aerospace Communications." Electro-Technology, May 1965, p. 40.

A-3 SIGNAL ATTENUATION AND NOISE CONTRIBUTION DUE TO RAIN AND CLOUDS - (Q_H and Q_N)

From the system equation, the combined loss of energy due to rain and clouds are accounted for by the two absorption factors--Q_H and Q_N--which are the absorption factors in the horizontal and vertical (normal) ray path direction, respectively, and the ambient temperature of the rain medium--T_r. In this study it is best to represent Q_H and Q_N as time statistics and this is easily done in terms of the rainfall rates for the region under consideration.

In modeling Q_H and Q_N, the contributions from clouds and rain will be considered spearately, i.e., $Q_H = Q_{HR} + Q_{HC}$ and $Q_N = Q_{NR} + Q_{NC}$.

Considering Q_{HR} and Q_{NR}, Holzer[1] presents a simplified method for determining absorption Q and the corresponding attenuation 10 log (1-Q)

$$\text{Attenuation (db)} = 10 \log (1-Q) = pqr \qquad \text{A-1}$$

where

Q = absorption expressed as a ratio (normalized percentage)

p = rainfall rate in mm/hr

q = value of attenuation (dependent upon frequency and rainfall rate) coefficient in db/km/mm/hr

r = the length of the path through the rainy medium in km. For temperate climates r for the vertical direction r_N is approximately 3 km. For the horizontal direction, the length of path through rainfall is related to rainfall rate by the following empirical equation:

$$r_H = 41.4 - 23.5 \log_{10} p$$

[1]Holzer, W., "Atmospheric Attenuation in Satellite Communications." The Microwave Journal, March 1965, p. 119.

Figure A-2a gives q as a function of frequency and for rain rates of 10 and 100 mm/hr. Attenuation coefficient q varies little with p. Accordingly, the median of the two curves will be used. Statistics on rainfall rates are shown in Figure A-2b for several locations. From these rain statistics, the values of q given in Figure A-2a, and Equations A-1 and A-2, the percentage of time a given Q_{HR} or Q_{NR} is exceeded can be determined. Figure A-3 shows values of attenuation Q_{HR} and Q_{NR} versus percentage of time exceeded for rain rates in the Washington, D. C., area. This area is typical of a temperate climate. Curves are presented for 4, 7 and 10 Gc/s. Below 5 Gc/s the effect is negligible. It is quite small up to 10 Gc/s. Q_{NR}, given in Figure A-3, is for a normal ray path. For other than normal signal paths, the values are increased by sec θ_s.

It should be emphasized that although the attenuation in the vertical direction Q_{NR} reduces the received signal strength, the attenuation in a horizontal direction Q_{HR} reduces the effect of potentially interfering signals. Thus, in some cases rain may be desirable. In any event, the two are offsetting effects in terms of signal-to-noise ratio and tend to reduce the effect of rain on the quality of signal received from a satellite.

Attenuation due to cloud absorption is given by the relation[1]

$$10 \log (1-Q_{HC}) = k_c \rho r$$

where

k_c = the attenuation coefficient

ρ = the water vapor content in gm/m^3

r = the ray path length through the clouds.

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[1]Holzer, Ibid.

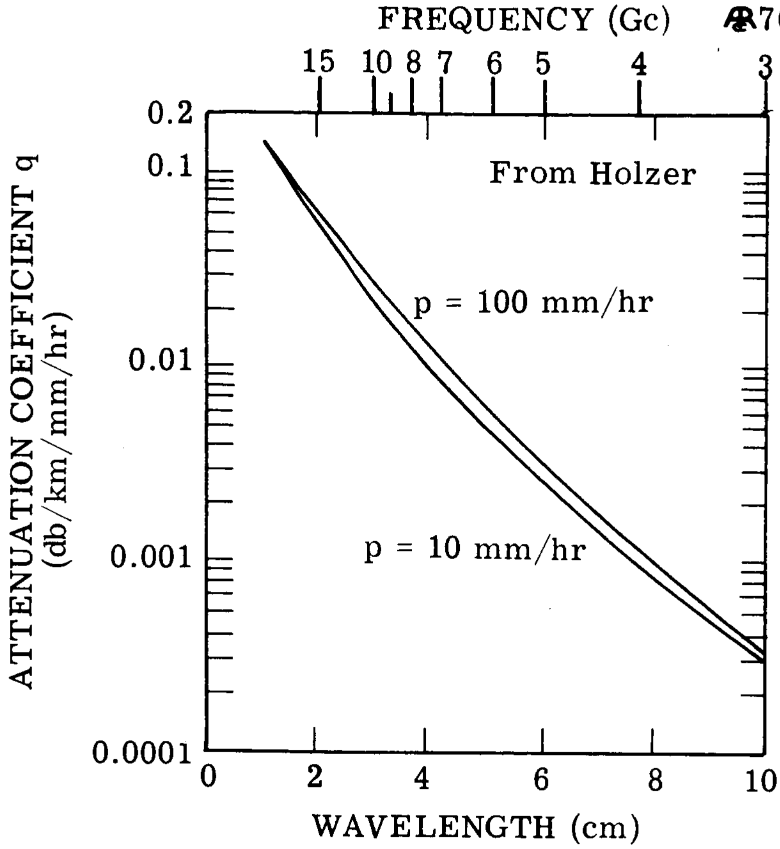

Figure A-2a. Q Versus Frequency and p.

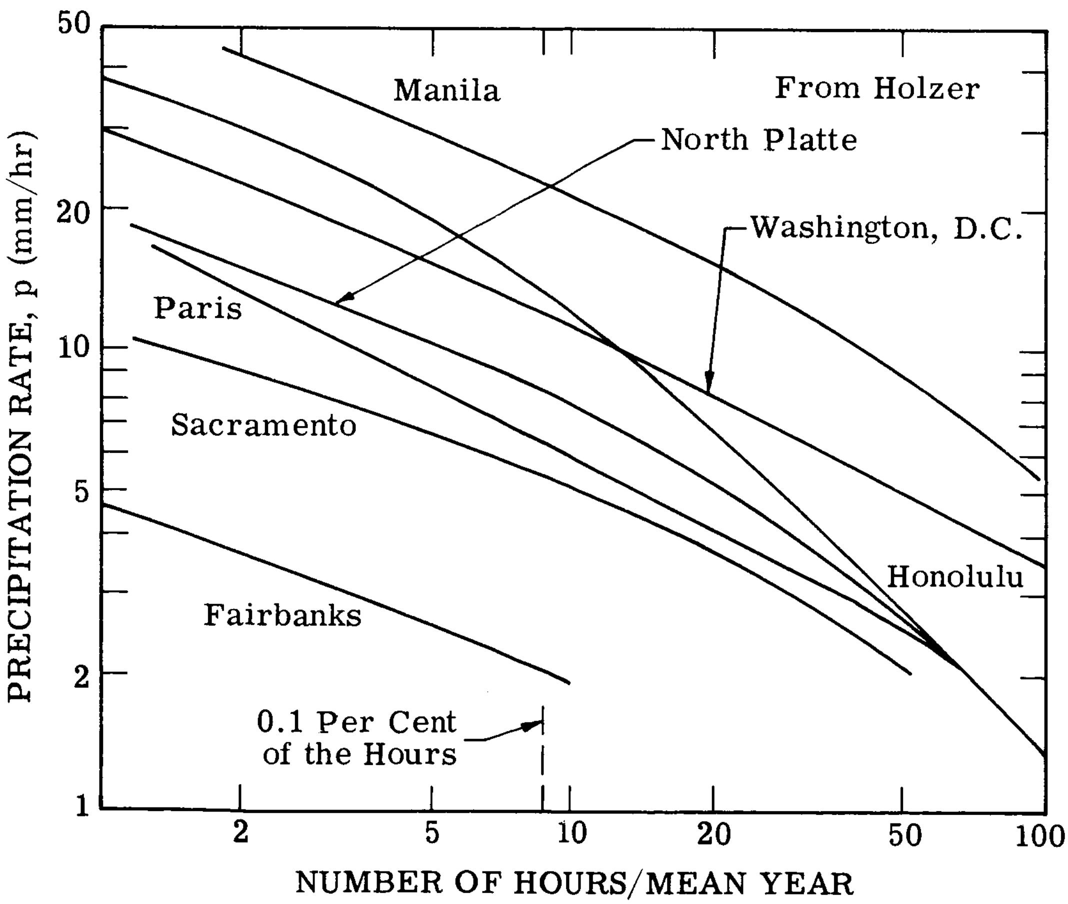

Figure A-2b. Factors Affecting Q_{HR} and Q_{HN}.

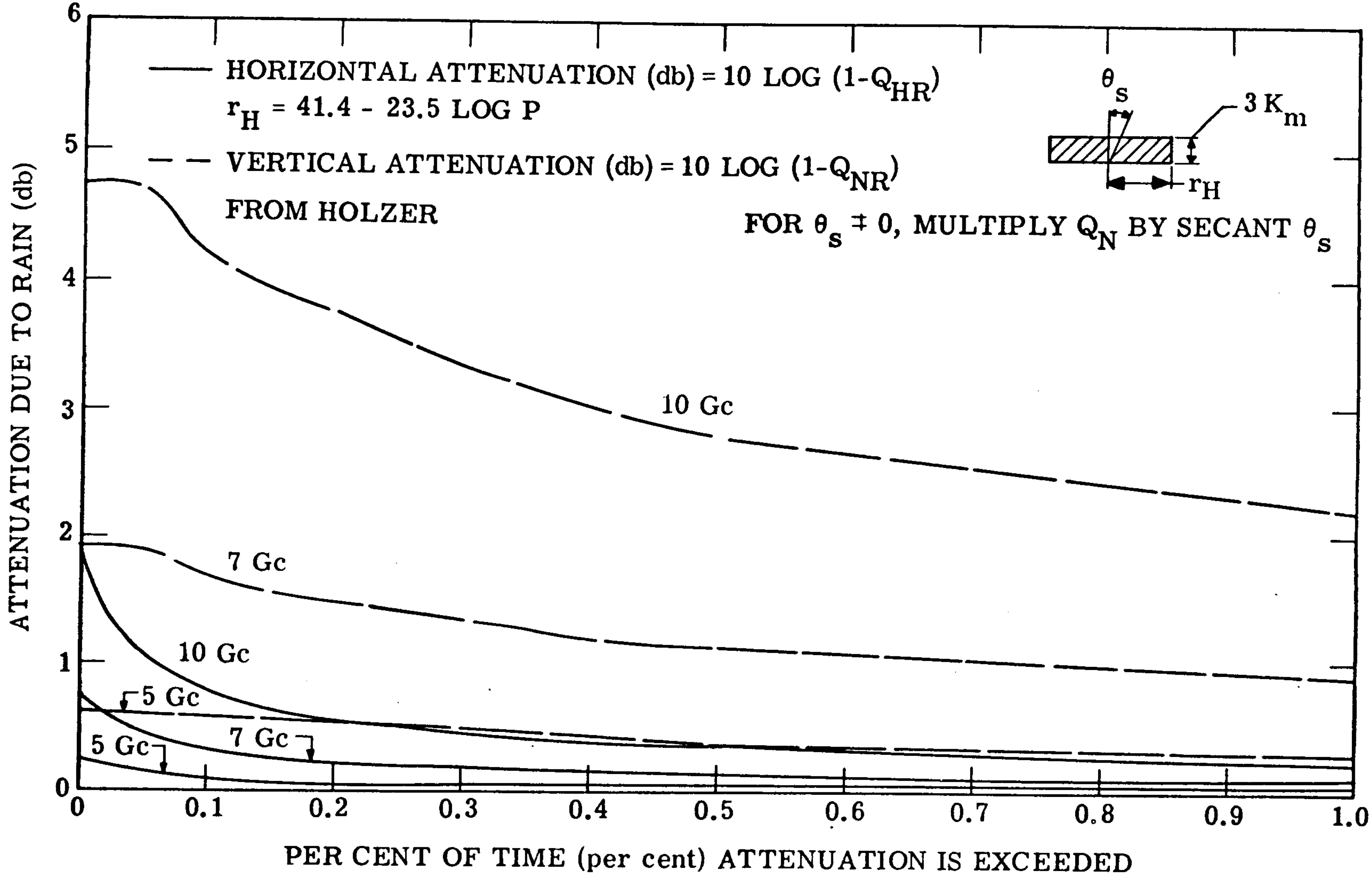

Figure A-3. Rain Absorption in a Temperate Climate, $\theta_s = 0$.

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A-4 FARADAY LOSS - POLARIZATION ROTATION

When a radio wave propagates in a magneto-ionic medium (example, the ionosphere and the earth's magnetic field), the plane of polarization rotates along the ray. The rotation of the plane of polarization is a result of the birefringent characteristic of the medium--that is, an incident electromagentic wave divides into two characteristic waves, the ordinary and extraordinary. These two characteristic waves can be thought of as two circularly polarized waves, one right-hand circularly polarized, the other left-hand circularly polarized. These characteristic waves travel different paths at different phase velocities and upon leaving the magneto-ionic medium (ionosphere) they have a phase difference leading to a rotation of the plane of polarization of the initially polarized wave. The amount of angular rotation of the plane of polarization after traversing the medium depends on the frequency of the incident wave and the physical characteristics of the medium along the ray path, such as the magnetic field and electron density. The total rotation of the plane of polarization is given by the expression:

$$\Omega = \frac{K}{f^2} \int_{\text{ray path}} NH \cos \alpha \, ds \qquad \text{A-3}$$

If the assumption is made that H cos α, sec X varies little with height and an average value is used,

$$\Omega \cong \frac{K}{f^2} NH \cos \alpha \sec X \int_{h_1}^{h_2} dh$$

k_c is a function of frequency and values for frequencies of interest are given in Table A-1. For a water vapor density of 0.3 gm/m^3, a vertical cloud extent of 6 km and an antenna elevation of 43° attenuation due to clouds is given in Table A-1. As shown in the Table, the attenuation is negligible being a maximum of .396 db at 12 Gc/s.

Duration of clouds in the horizontal direction varies and will have a small effect on the system.

For computational purposes, Q_H and Q_N will be determined by Q_{HR} and Q_{NR} since Q_{HC} and Q_{NC} will be negligible in comparison for the elevation angles of interest.

TABLE A-1

ATTENUATION DUE TO CLOUDS FOR AN ELEVATION ANGLE OF 43° AND WATER CONTENT OF .3 gm/m^3

Frequency (Gc/s)	Coefficient of Attenuation (k_c) (db/km/gm/m^3)	Ray Path Length (43° elev.) (km)	10 log $(1-Q_{HC})$ (db)
4	.026	8.8	.0686
6	.043	8.8	.1133
8	.065	8.8	.1710
10	.095	8.8	.2500
12	.150	8.8	.3960

In the above equations:

Ω = polarization rotation angle, radians

f = wave frequency, cps

N = electron density, elec/m^3

H = magnetic field intensity, amp-turns/m

α = angle between the magnetic field and the direction of propagation

ds = element of path length = sec X dh

X = angle between ray and the vertical at the satellite location

dh = incremental altitude

and

$$K = \frac{e^3 \mu_o}{8\pi^2 m^2 C E_o} = 2.97 \times 10^{-2}, \text{ MKS units}$$

where

e = electron charge

μ_o = permeability of free space

C = velocity of light

m = mass of electron

E_o = permittivity of free space

These equations are valid under the following conditions, all of which are fulfilled for the frequencies of interest in this report.

(1) The operating frequency is large compared to the collision frequency, the highest plasma frequency in the ionosphere, and the gyro frequency;

(2) The ordinary and extraordinary rays follow essentially the same path;

(3) The quasi-longitudinal approximation is valid. (The quasi-longitudinal approximation is a modification of the equation for

the refractive index that holds when a significant component of the magnetic field is in the same direction as the direction of propagation. The quasi-longitudinal approximation is, as a rule, fulfilled for angles where $\alpha < 80°$ if the frequencies considered are significantly higher than the plasma or giromagnetic and collision frequencies.)[1]

If the electron density of the ionosphere remained constant and the magnetic field were a known constant value, the problem of the rotation of the plane of polarization could be overcome by rotating the axis of polarization of either the transmitting or receiving antenna until maximum coupling was obtained. However, it is well know that the ionosphere density varies with time in a variety of ways. Therefore, it is not possible to accurately predict the amount of rotation. Since the exact amount of rotation of a linearly polarized wave cannot be determined even at a specific frequency, circular polarization or special reception techniques may be necessary, the need depending to a large extent on the frequency of operation desired.

It can be seen in Equation A-3 that the amount of polarization rotation is inversely proportional to the frequency squared. Thus, it may be expected that at some point in the spectrum, as the frequency of operation is increased, the rotation will become negligible. A model atmosphere was assumed and the amount of rotation computed for the case of a receiving antenna located at 40°N latitude directed toward a synchronous satellite located 22,500 miles from the equator at the same

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[1]Namazov, S. A., Determination of Electron Density is the Ionosphere by Analysis of Polarization Fadings of Satellite or Rocket Signals, NASA Washington, D. C., October 1962.

longitude as the receiver station. This configuration results in an elevation angle of the antenna of $\sim 43°$ or a θ_s of 47°.

Based upon the work of Harold Pratt as reported in the <u>IRE Transactions on Communications Systems</u>[1], it is reasonable to assume the following value for the magnetic field H and electron density N in the ionosphere:

$$\overline{H \cos \vartheta} = 30 \ \frac{\text{amp-turns}}{\text{meter}}$$

$$N = 2.8 \times 10^{12} \ \frac{\text{Electrons}}{(\text{meter})^3}$$

The above values were assumed to exist between 232 and 370 km and to be zero elsewhere.

Using the values of rotation computed from Equation A-3 for the frequencies of interest in this report, loss due to polarization mismatch was calculated using the following relationship:

$$1-F_L = \cos^2 \Omega$$

which in db is expressed as

$$\text{Loss (db)} = 10 \log (1-F_L) = 20 \log \cos \Omega$$

where F_L = normalized percentage energy lost due to polarization mismatch. The following values of loss are possible if both the transmitting and receiving antennas are linearly polarized and if the ionosphere electron density and magnetic field are not greater than the assumed values.

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[1]Pratt, H. J., "Propagation, Noise and General Systems Considerations in Earth Space Communication." <u>IRE Transactions on Communications Systems</u>, December 1960.

TABLE A-2

FARADAY LOSS IN A STANDARD ATMOSPHERE--CASE I

(Linear Polarization at Transmitting and Receiving Antennas)

Frequency (Gc/s)	Ω (Radians)	10 log (1-F) (db)
.200	$> \pi/2$	Can be infinite if $\Omega = \pi/2$
.400	$> \pi/2$	Can be infinite if $\Omega = \pi/2$
.600	.961	4.83
.800	.541	1.34
1.0	.346	.532
2.0	.086	.131
4.0	.021	.002
6.0	.009	0
8.0	.005	0
10.0	.003	0
12.0	.002	0

At the lower frequencies the rotation angle exceeds $\pi/2$ and it is possible that the polarization of the received wave will be orthogonal to the receiver antenna polarization and the loss can be infinite. Thus, at these frequencies circular polarization most likely will be used for either the transmitting or receiving antennas. At the higher frequencies the loss is insignificant and linear polarization of both the receiving and transmitting antennas will not cause significant loss.

In considering the possible signal loss due to polarization mismatch, three antenna configurations are considered in the system analysis.

They are:

Case I - Both transmitting and receiving antennas are linearly polarized.

Case II - The transmitting antenna is circularly polarized and receiving antenna is linearly polarized.

Case III - Both transmitting and receiving antennas are circularly polarized.

The frequencies considered for possible use in this report ranged from approximately 200 Mc/s to 12 Gc/s. Since polarization rotation is a function of frequency, the type of antenna polarization configuration (Case I, II, or III) depends on the portion of the frequency spectrum at which the system is operating. Each antenna configuration has associated with it a loss. For example, at low frequencies configuration II or III may be used, and the associated loss will be -3 db for Case II and zero for Case III. For mid-frequencies (600 Mc/s to 4 Gc/s) configuration I, II, or III may be used. The loss for Case I is taken from Table A-2. The loss for Case II is 3 db and the loss for Case III is zero. At the higher frequencies, Case I is used exclusively. The effect is zero. As pointed out, in certain of the frequency ranges alternate configurations are possible. These alternates were considered. The difference in cost of the different configurations was considered in the computation of total system cost.

A-5 IONOSPHERIC TRANSMISSION LOSS

Besides losses due to Faraday rotation, the principal concern in transmitting signals from a stationary satellite is dispersion caused by the variation of the velocity of propagation with frequency (i.e., the signal components of different frequencies experience differing phase shifts which can result in significant distortions of the composite signal wave shape). This effect, if severe enough, can limit the amount of bandwidth available for utilization in a communications system.

A number of commentators have attempted to definitize the nature of the loss which may be expected from the dispersive effects of the ionosphere [1, 2, 3]. An accurate analysis is dependent on a thorough knowledge of the ionospheric transmission characteristics as a function of frequency, modulation, and look angle. Adequate information on these factors does not appear to be available. Several estimates of transmission bandwidth as a function of frequency are indicated in Figure A-4. As is apparent, there is considerable difference. The optimized FM system would require an RF bandwidth of about 32 Mc/s, and about 48 Mc/s for a system using FM feedback. According to this the highest carrier frequency usable would be those indicated in the Table below:

TABLE A-3

IONOSPHERIC CONDITION	F(Standard)	T(Feedback)
Reinhart et el		
Minimum Electron Density - 90°	370 Mc/s	490 Mc/s
Minimum Electron Density - 20°	420 Mc/s	750 Mc/s
Maximum Electron Density - 90°	750 Mc/s	1,200 Mc/s
Maximum Electron Density - 20°	1,300 Mc/s	1,800 Mc/s
Gould	800 Mc/s	950 Mc/s

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[1] Swayze, D. W., "On the Transmission Characteristic of the Ionosphere." Proceedings of IEEE Annual Communication Conference, Boulder, Colorado, June 7-9, 1965.

[2] Reinhart et el, "Multiple Access for Communications Satellites." Stanford Research Institute Report.

[3] Gould, R. G., "A Study of the Influence of Commercial Communication Requirements on the Design of Communication Satellites." SRI Report 3390, January 1962.

In addition to the above, Staras[1] makes the comment that under the condition of using FM and a modulation index of ten, it would be necessary to use a frequency higher than 1,000 or even 3,500 Mc/s.

It is evident that there is not yet sufficient information to make a confident prediction as to the limitation on bandwidth due to the ionosphere. It is important that these limitations be determined as they will play a key factor in determining at what freqneucy wide-band communications from satellite may be used.

Finally it should be point out that as a function of satellite height, the dispersion effects should be counted out, whatever their exact nature may be.

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[1] Staras, H., "The Propagation of Wide-Band Signals Through the Ionosphere." IRE, July 1961, p. 1211.

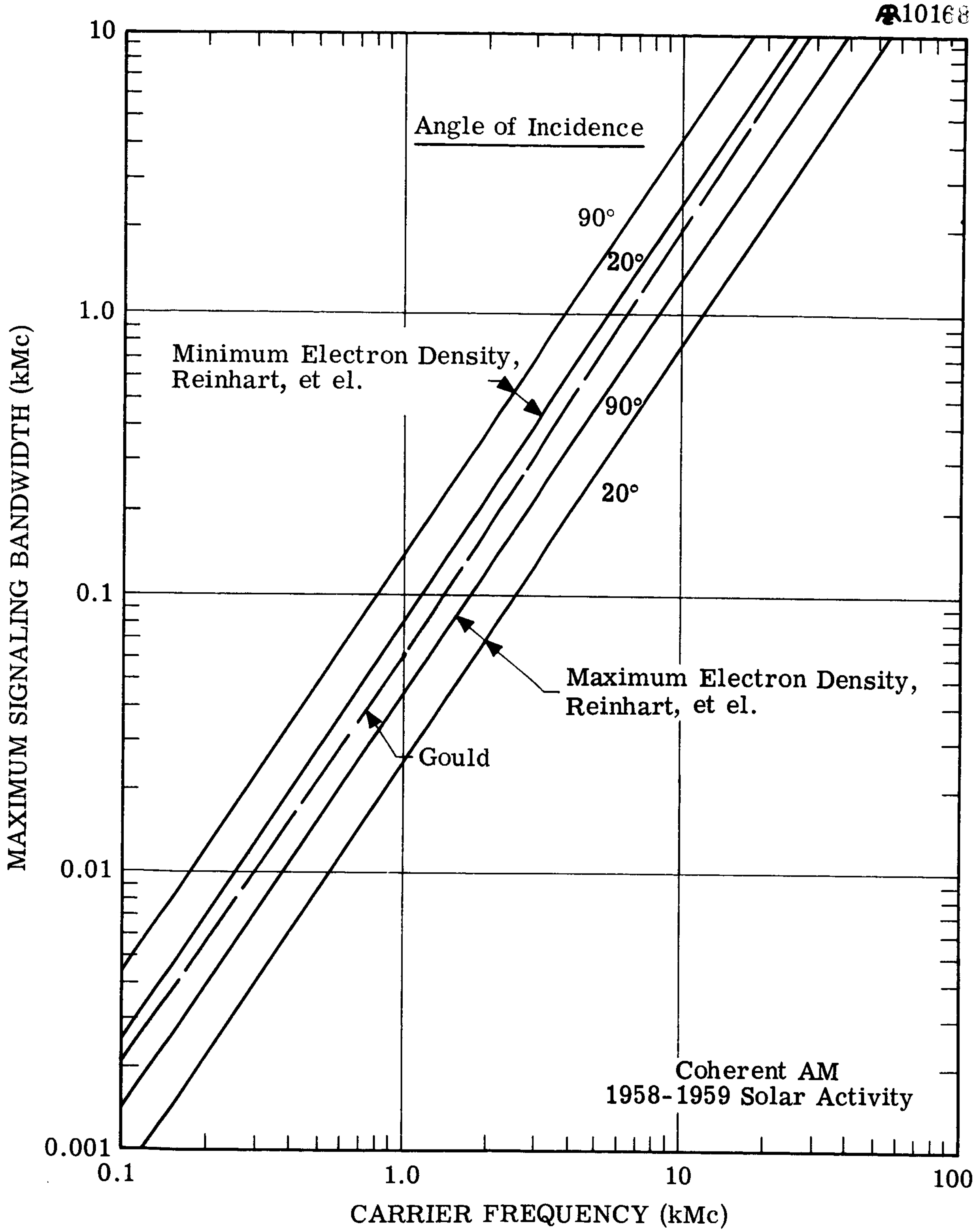

Figure A-4. Estimate of Transmission Bandwidth of the Ionosphere.

APPENDIX B

ENVIRONMENTAL NOISE

B-1 GENERAL

As discussed in this Appendix, the environmental noise is specified at a receiving installation as a brightness temperature over some solid angle. The contribution of this brightness temperature to the antenna temperature is ascertained by weighting the brightness temperature in a given direction by the antenna gain in that direction. The total contribution from a particular source is then determined by summing up or integrating the differential contributions.

In the discussions to follow, the various types of noise are considered as average brightness temperatures over the solid angle which they subtend. The antenna temperature can then be found as the product of the average brightness temperature and the average antenna gain over the solid angles.

B-2 BACKGROUND COSMIC NOISE TEMPERATURE--(T_{CK})

The values of T_{CK} depend upon the orientation of the receiving antenna with respect to the galactic center. As the orientation changes, T_{CK} varies between the limits shown in Figure A-1b. As can be seen from the Figure, T_{CK} decreases rapidly with frequency, becoming negligible at 1 Gc/s. For system evaluation, the values of T_{CK}, which are in the middle of the T_{CK} range, were used since the higher values are only obtained when the antenna is pointed at the galactic center.

B-3 DISCRETE SOURCES

The contribution to the total antenna temperature of an earth-based receiver from discrete noise sources (sun, moon, radio stars, etc.) is determined by (1) the antenna gain in the direction of the noise source, (2) the noise power density from each discrete source, and (3) the angle subtended by the discrete source. Discrete sources of primary interest (those which may produce sufficient noise to be significant) are the sun, moon and a few radio stars.

(1) Sun

Of the discrete sources, the sun is the largest potential contributor to the antenna temperature. Because of its small angle of subtension, it is a factor only when in the main lobe of the antenna. For discrete sources, the contribution to effective antenna temperature is a function of the antenna gain to a greater extent than for distributed noise sources. The noise temperature contribution and per cent of time the sun is within the beam can be determined as a function of the antenna gain.

The effective antenna temperature contribution from the sun is given by

$$T_{SA} = T_{SB}\frac{\Omega_S}{\Omega_B} \qquad \text{B-1}$$

where T_{SA} = noise contribution from the sun in °K

T_{SB} = brightness temperature of the sun in °k

Ω_S = solid angle subtended by the sun in steradians ($\cong 6.3 \times 10^{-5}$ steradians)

Ω_B = solid angle of the antenna main beam in steradians.

Ω_B, in steradians is related to the antenna beamwidth by the relation:

$$\Omega_B = \frac{\theta_B \varphi_B}{3,280}$$

where θ_B and φ_B are the antenna beamwidths in the θ and φ direction

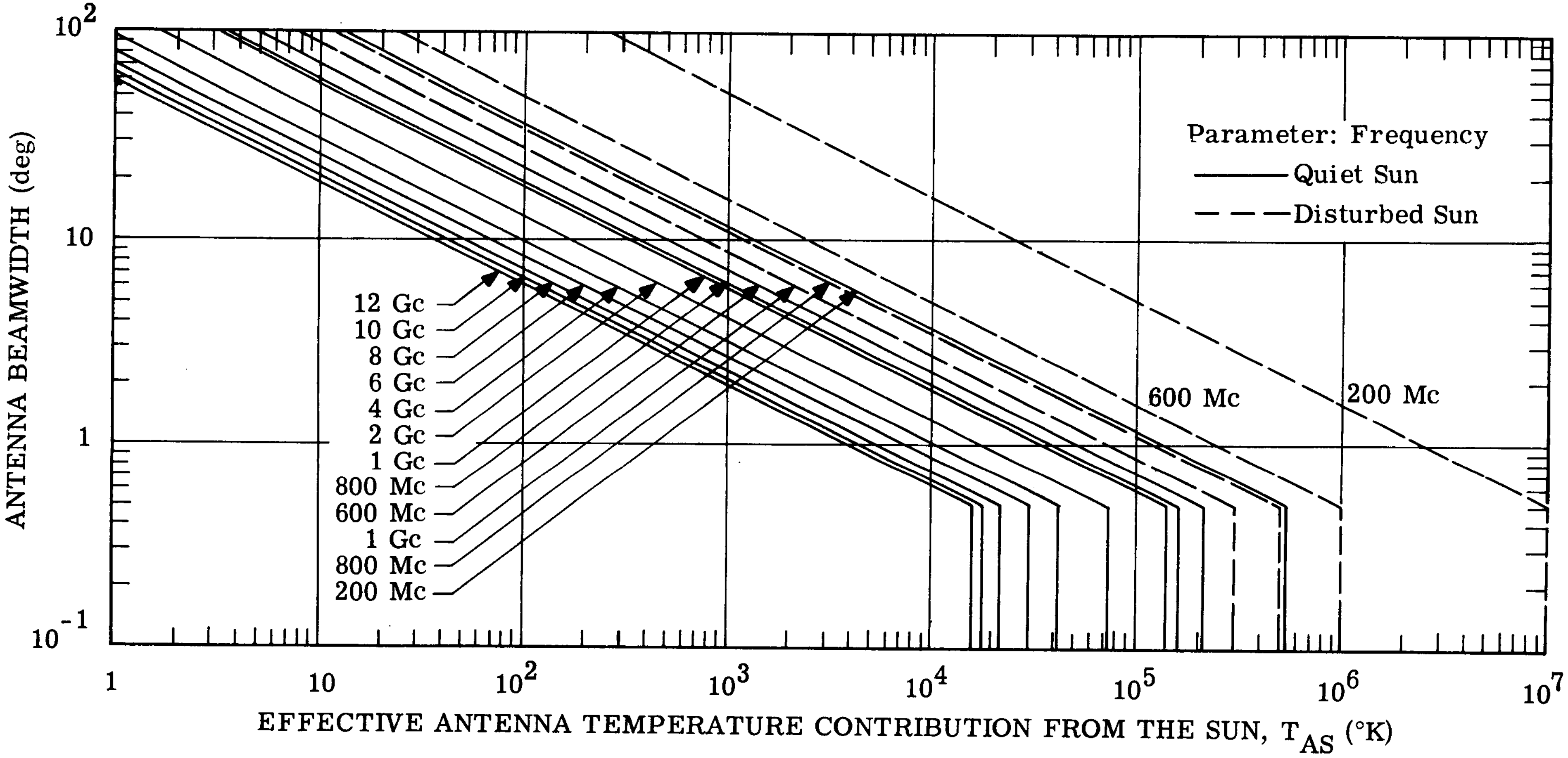

Figure B-1. Effective Antenna Temperature Contribution from the Sun for Antennas with Symmetrical Patterns.

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respectively, and are expressed in degrees. For the case of a symmetrical pattern antenna, such as a parabola, $\theta_B = \varphi_B$. Figure B-1 shows the sun's antenna noise contribution as a function of frequency and antenna beamwidth for two conditions of the sun. These conditions are the quiet sun and the disturbed sun. Figure B-1 was developed from brightness temperature data given in the literature.[1]

One limitation imposed on the analysis of the effects of noise from the sun was a lack of data on the time distribution of noise power radiated. Because of the complexity of the solar radio spectrum, it is difficult to establish statistics on the percentage of time the sun is disturbed. It is known, however, that the disturbances are more frequent and intense near sun spot maximum.

In addition to the magnitude of the antenna temperature contribution from the sun, it is meaningful to consider the per cent of time the sun will be in a position to effectively increase the antenna temperature. In determining this, the assumption is made that only the contribution through the main beam is significant. Figure B-2 shows the total per cent of time the sun is within the antenna beamwidth as a function of the antenna beamwidth. This curve was computed using data from a nautical almanac (1964) showing the sun's declination (angular position relative to the celestial equator) throughout the year. Assuming that the receiving antenna is located at the same longitude as the synchronous satellite and at a specific latitude (say 40°) the declination of the antenna with respect to the equator can be computed. The declination will be different for each antenna latitude and varies from 0° declination

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[1]Filipowsky, R. F. and Muehldorf, E. I., Space Communication Systems. Prentice Hall Inc., 1965.

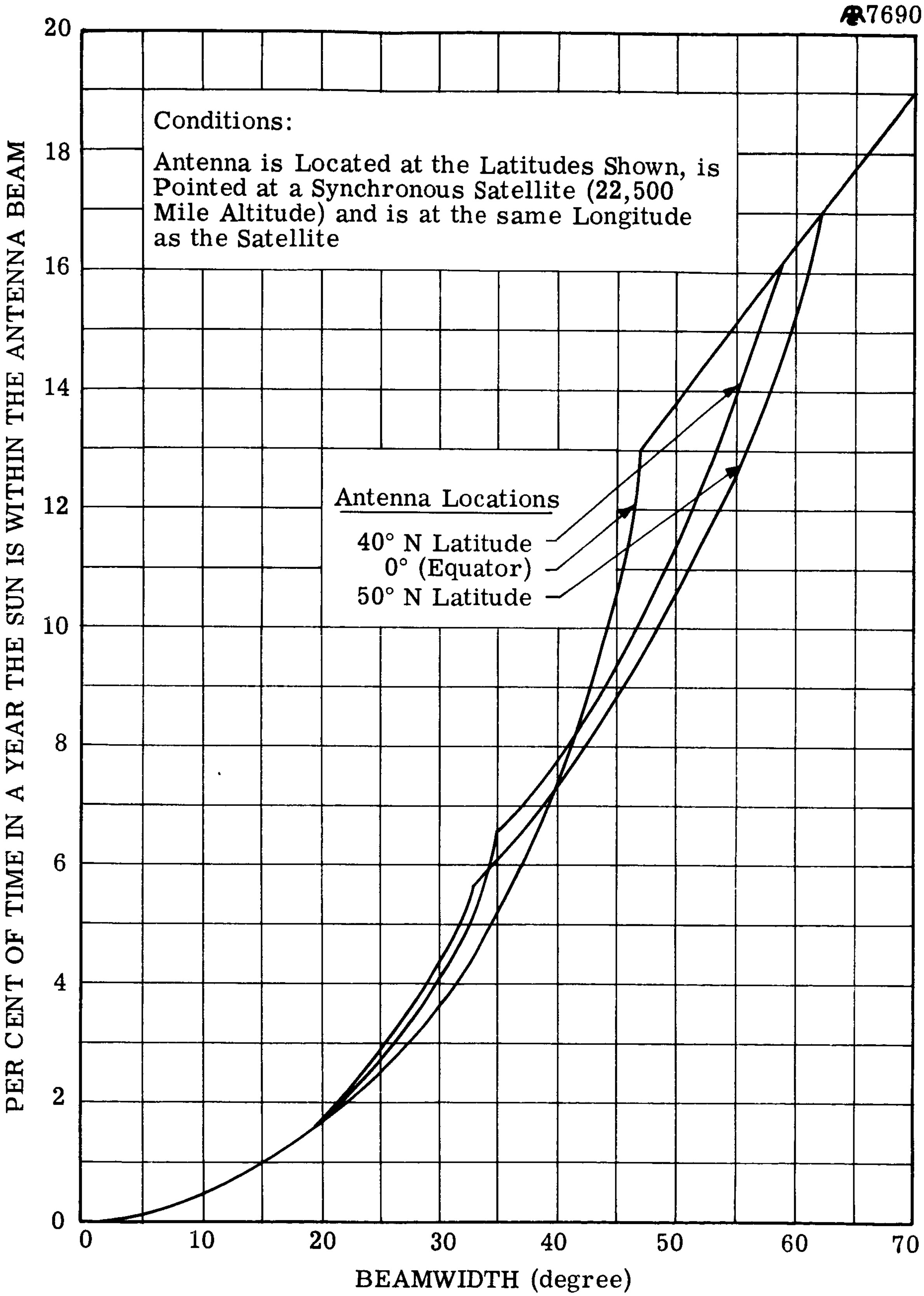

Figure B-2. Per Cent of Time in a Year the Sun is Within the Antenna Beam.

if the antenna is at the equator to approximately -8° declination when the antenna is at a latitude of 70° N. The curves shown in Figure B-2 are for antenna declinations of 0°, -6° and -7°, corresponding to antenna locations at the equator, 40° N latitude and 50° N latitude, respectively.

The curve in Figure B-1 is used in conjunction with the curve in Figure B-2 to determine the maximum or minimum antenna temperature contribution from the sun for specific beamwidths and the per cent of the days of the year and hours of the day the sun is within the beamwidth.

An example of how the curves can be used is as follows:

Receiving antenna location - latitude 40° N, longitude same as satellite

Beamwidth - 15°

Frequency - 1 Gc/s

From Figure B-1 the antenna noise temperature contribution from the sun at 1 Gc/s and a beamwidth of 15° lies between 1.5×10^2 and 3.4×10^2 °K depending upon the condition of the sun.

The antenna location is 40° N latitude and the antenna beamwidth is 15°. From Figure B-2 it is seen that the sun is within the beamwidth approximately one per cent of the hours in a year.

Thus, one per cent of the hours in a year (or approximately one hour per day or 76 days of the year) the sun's contribution to the antenna noise temperature will lie between 1.5×10^2 and 3.5×10^2 °K. It is quite obvious that the noise contribution from the sun is not a random phenomenon, but is quite predictable in that the specific days of the year a 15° antenna beam will be looking at the sun can be determined.

Also, which hours of the day the antenna will be looking at the sun is predictable. Therefore, the per cent of time the sun will contribute noise to the total antenna noise temperature can be associated with specific times at which the noise will occur and should not be interpreted as random interference that could occur at any time.

(2) Radio Stars

Superimposed on the general background radiation due to the galaxy are numerous discrete sources, each generally less than 1° in extent. Since the majority of these sources cannot be identified with visible objects, they are known as radio stars.

The strongest of these sources show a tendency to occur near the plane of the galaxy. In general the noise contribution from a single radio star is minor relative to the galactic background unless extremely high-grain, narrow-beam antennas are pointed in the direction of the star. The relative geometry of the synchronous satellite and ground receiving antenna is such that the declination of the receiving antenna with respect to the celestial equator varies between -8° and +8° when the antenna location varies between 70° N latitude and 70° S latitude.

Thus, the portion of the celestial sphere the antenna sees lies between the limits -8° and +8° declination. The most intense radio stars (Cygnus A,Cassiopeia A, etc.) lie outside this interval. Since the ground antenna beam does not intercept significant radiation from discrete radio stars, the contribution from these sources may be neglected.

(3) Moon

The moon as a contributor to the total antenna temperature is not particularly significant due to the low level radiation (approximately 230° K brightness temperature at frequencies from 300 Mc/s to 10 Gc/s) assuming the angle subtended by the moon is 0.5°. The only time the brightness temperature would be equal to 320° K would be if an antenna beamwidth of 0.5° or smaller were used. If the beamwidth is 5°, the effective antenna temperature contribution from the moon drops to 2.3° K and if it were 10° the temperature is ≈0.6° K. These temperatures would only occur during the small per cent of time the moon would be within the antenna beamwidth. Since the radiation level and the per cent of time the source would be within the beamwidth are both relatively small, the moon's contribution to the total antenna temperature may be ignored.

B-4 INDIGENOUS NOISE (T_I)

At the present time, the available data on indigenous noise are limited and outdated. The Department of Commerce is currently establishing a program to obtain extensive indigenous noise data and develop meaningful noise statistics. The current standard noise data are found in the ITT Handbook.[1] These data as indicated in Figure B-3 present the noise in terms of equivalent field strength. Indigenous noise values are given up to 1.0 Gc/s for urban or city locations. Urban indigenous noise decreases exponentially with frequency. On a log-log plot it is

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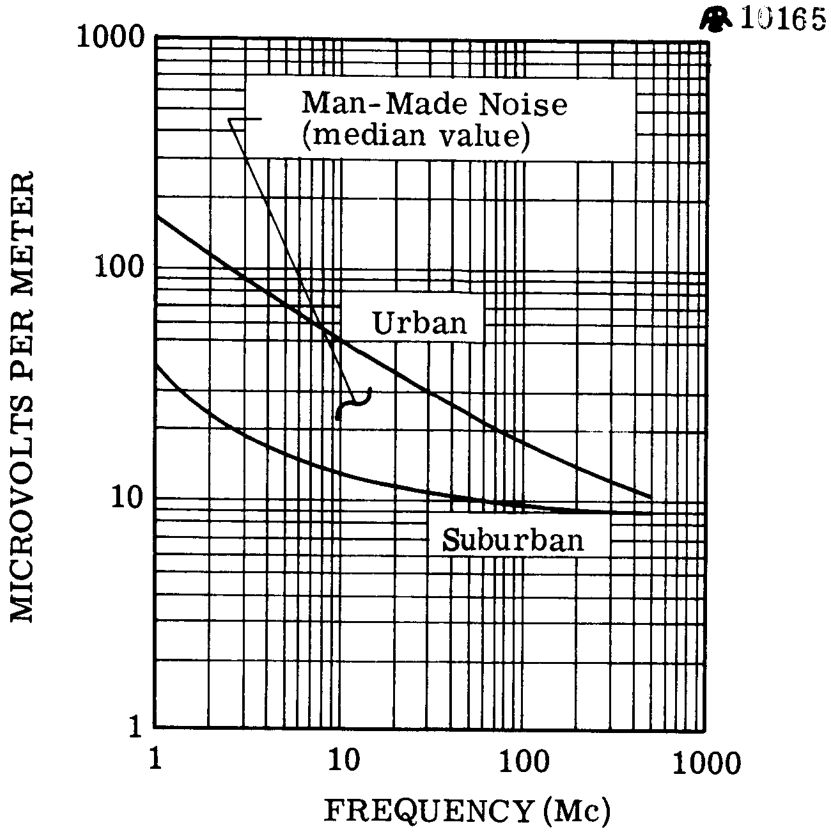
[1]Reference Data For Radio Engineers, International Telephone and Telegraph Corporation.



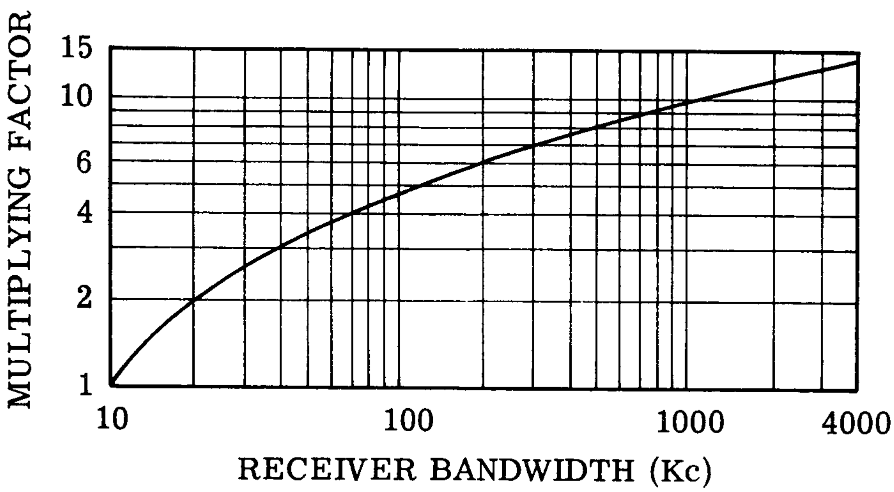


Figure B-3. Indigenous Noise Bandwidth Correction Factor.

linear. By extending this line, of the log-log noise versus frequency plot beyond 1 Gc/s, values were extrapolated out to 12 Gc/s.

The ITT data are presented in terms of equivalent noise field strength (E_i). This can be converted to an equivalent brightness temperature through the relation

$$T_I = \frac{E_i^2}{z_o} \frac{\lambda^2}{4\pi K(\psi/2)} \frac{K_n^2}{B} \qquad \text{B-2}$$

where E_i is the noise field strength given by the ITT data for a 10 kc bandwidth, λ is wavelength, z_o is the impedance of free space which is 120π ohms, K is Boltzman's constant, $\psi/2$ for small angles is the ratio of the angle radians subtended by the indigenous noise at the antenna to the total solid angle, 4π and K_n is a correction factor to convert the basic field strength data to field strength for other than 10 kc.

Values of T_I determined from Equation B-2 are given in Table 4.3.1 for ψ = .18 radians or 10°, a value of E_i which corresponds to that which is not exceeded at approximately 60 per cent of the location, and B = 4 Mc/s. Values are given for maximum indigenous noise assumed appropriate for urban locations and 10 per cent urban noise considered appropriate for suburban locations. The relationship between Kn^2 and frequency is also given in Figure B-3.

In the determination of receiving system cost, indigenous noise is an important factor. Computations have been made for the various values shown in Table 4.3.1. The variation of receiver cost with the type of location can be established as well as functional relationship between cost and indigenous noise.[1]

[1] Values for indigenous noise given in the ITT data are for bandwidths of 10 kc. To extend the data to higher bandwidths, the 10 kc values must be multiplied by the factor given in Figure B-3. This factor can be used to correct indigenous noise expressed as either power density or equivalent brightness temperature.

Sixty per cent of the receiving locations will have values equal to or less than those given in Table 4.3.1. Seventy per cent of the locations will have noise less than 1.30 times these values and 90 per cent of the location will have noise less than 4.25 times these values.

In the selection of an antenna location for a particular receiving site, the surrounding terrain or structure could be used to reduce the indigenous noise. The values given in Table 4.3.1 would be representative of a much higher percentage of well designed receiver locations, than locations which are selected at random. A second factor is that the major portion of indigenous noise results from poorly insulated automobile ignition systems. At the present ignition systems are much better insulated than when the ITT data were taken.

Indigenous noise as given in Table 4.3.1 will be representative of 90 per cent or more of the possible locations by 1970 if good use is made of the surrounding terrain.

B-5 AMBIENT TEMPERATURES (T_{atm}, T_{ION}, T_{RF}, T_g, T_{Qr})

The physical temperature of all absorbing mediums determine the amount of noise generated by these media. These absorbers and their corresponding ambient temperatures are: the atmosphere - T_{atm}, the ionosphere - T_{ION}, rain - T_{Qr}, the earth - T_g, and the antenna feeder system - T_{RF}.

The noise radiated by these absorbers is a linear function of the ambient temperature expressed in degrees Kelvin. An ambient temperature change of 70° Fahrenheit to 0° Fahrenheit results in a change of the absolute or Kelvin temperature of the medium of 291° to 251°. This is a change of 13.8 per cent. A large temperature change therefore does not alter the noise generating properties of the medium to any great extent. The ambient temperature will change diurnally and yearly, but should not change the noise environment appreciably.

In the system under consideration, a given standard of service will be demanded a high percentage of time. For computational purposes, all ambient temperatures are assumed to be 290° K, which is about 70° F. Ambient temperatures above this value will be experienced a small percentage of time, but the absolute temperature will change little on a percentage basis.

APPENDIX C

MODULATION ANALYSIS

C-1 MODULATION TECHNIQUES

The techniques other than standard vestigial sideband which might be used for transmitting television should be capable of a power-bandwidth trade-off. To keep cost down, the technique should not be excessively complicated. The logical choices of possible modulation systems are frequency modulation (FM) and pulse code modulation (PCM). These two modulation systems have been considered for satellite communication ahd their relative merits are discussed in the literature. It should be pointed out that PCM comes very close, in channel information content, to the theoretical limits of information theory. FM, while not as potentially efficient, is a much simpler system.

Figure C-1 gives the block diagram of a PCM system. At the point of origination, the analog waveform is sampled at the rate 2b/sec, where b is the bandwidth of the waveform being sampled. Each sample is compared with L possible coding levels. The level closest to the value of the sample is selected and n pulses are coded to represent the discrete level L. For a two level code (0 or 1) the relation between the discrete levels and number of pulses (n) per analog sample is

$$\log_2 L = n$$

The binary pulses from the coded output are then either transmitted as AM or are used to modulate a phase reversal carrier system. The pulses can be transmitted in double sideband (DSB) or

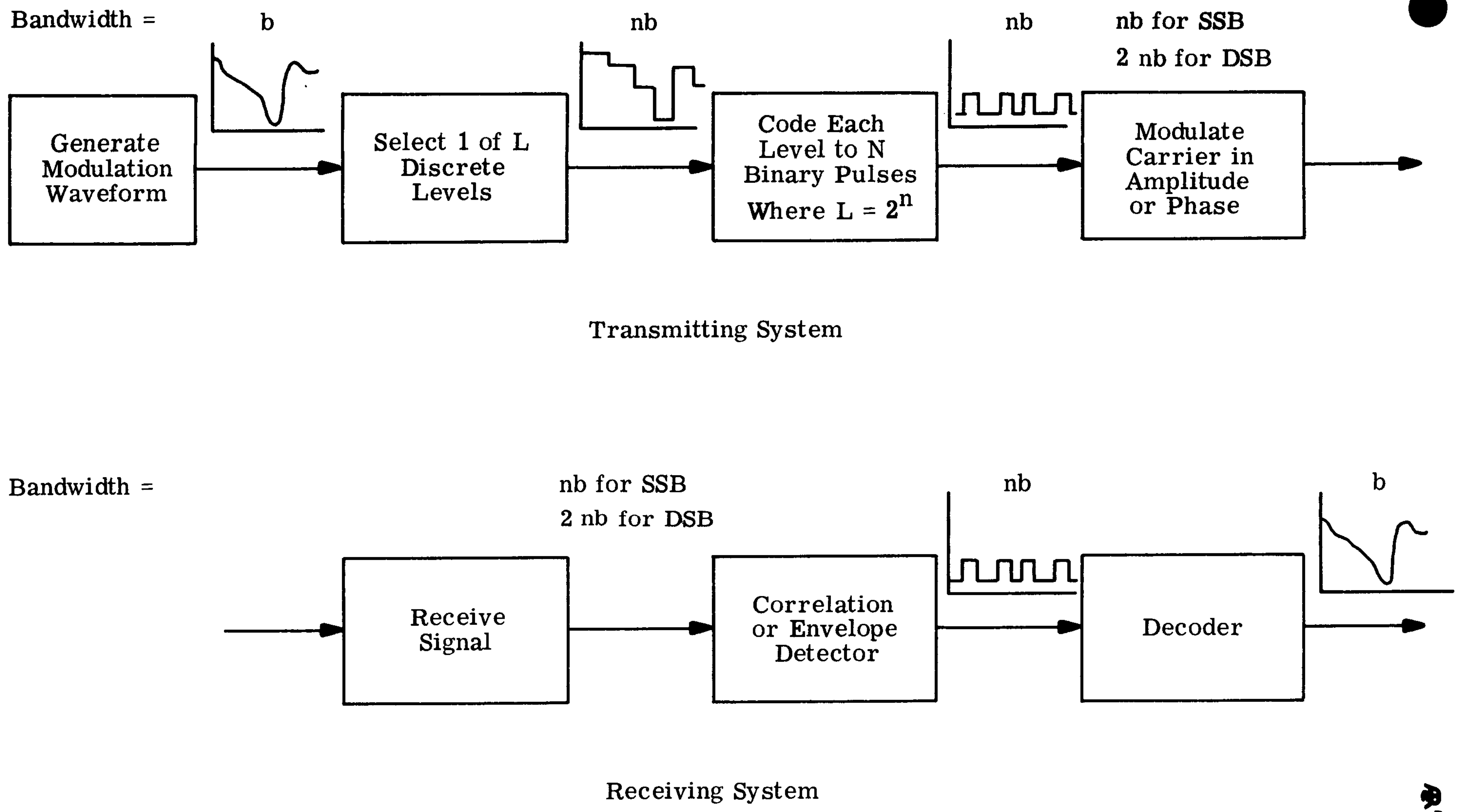


Figure C-1. PCM System Block Diagram.

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single sideband (SSB). For the DSB case the RF bandwidth is $B_{RF} = 2nb$, and for SSB, $B_{RF} = nb$. For SSB, either a vestigial sideband or synchronous detection system must be used. Due to the selection of a discrete level, quantization noise is effectively added to the signal at the coder. The ratio of signal to quantization noise is related to the number of pulses per analog sample n as follows:

$$Q = \frac{3}{2} (4) n \qquad \text{C-1}$$

At the receiver the pulses, in the form of AM or PM, are detected to give the binary video information and are then decoded. Due to the random nature of noise and the decoding process itself, a signal-to-noise improvement is realized in going through the decoder. This improvement is in the form

$$10 \log (S/N)_o = 2.2 \ (S/N)_{p.d} \qquad \text{C-2}$$

where

$(S/N)_{p.d}$ is referenced to the total predecoder bandwidth (nb).

As can be seen from Equation C-2, the improvement is exponential in form and depends entirely on the predecoder signal-to-noise ratio. It should be pointed out that Equation C-2 is valid only for $(S/N)_{KTnb} \geq$ 14 db. Where KTnb describes the noise in the total RF bandwidth. Below this threshold the given amount of improvement is not realized. If DSB with envelope detection is used, the predecoder signal-to-noise is 3 db less than the RF signal-to-noise when both are referenced to the same bandwidth. For vestigial sideband, both are the same, and for synchronous detection a 3 db improvement is realized. In Figure C-1 the major receiver costs directly associated with PCM are the decoder and the synchronous detector, if it is used.

The block diagram of a standard FM receiver is shown in Figure C-2. The improvement factor for the FM modulation system is of the form

$$(S/N)_o = \frac{3}{2} M^2 \; (S/N)_{RFb} \qquad \text{C-3}$$

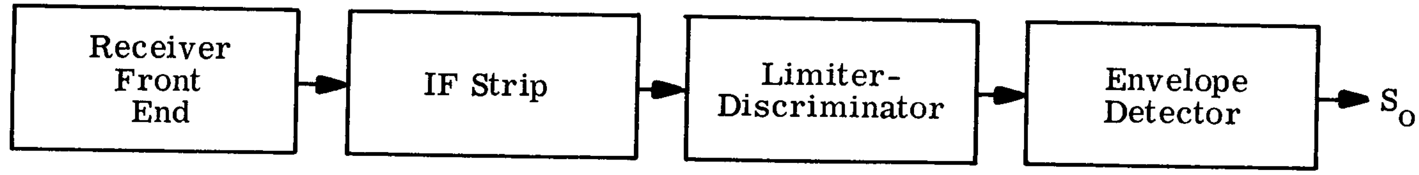
where M is the modulation index and $(S/N)_{RFb}$ is the pre-limiter signal-to-noise considering only the noise in the baseband, (b). The improvement factor is $\frac{3}{2} M^2$ and both signal-to-noise ratios are referenced to the same noise band. The total required radio frequency band required for FM is given by

$$B_{RF} = 2\ (1 + M)\ b \qquad \text{C-4a}$$

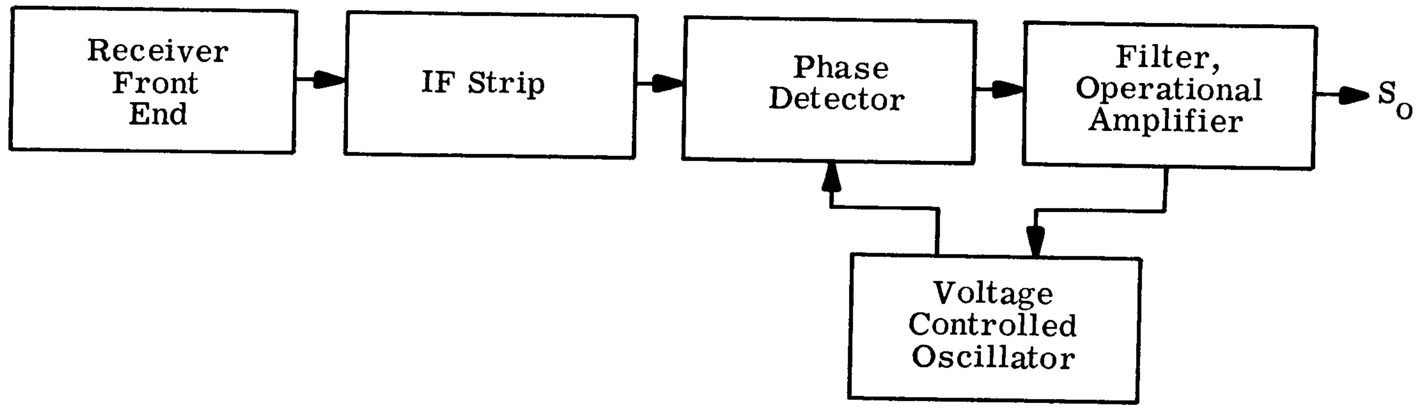
and the input signal-to-noise considering the noise in the total RF band is

$$(S/N)_{in} = \frac{1}{2(1 + M)} \; (S/N)_{RFb} \qquad \text{C-4b}$$

The improvement given in Equation C-3 is only valid for $(S/N)_{in} \geq 12$ db, unless a threshold reduction technique is used. A review of the literature indicates that this appears as a conservative value of FM threshold.



Standard FM Receiver



FM Phase Lock Loop Receiver

Figure C-2. Block Diagrams of FM Receivers.

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C-2 COMPARISON OF PCM AND FM FOR SATELLITE TELEVISION

In studying the advantages and disadvantages of the proposed techniques, an investigation of the system operation in the vicinity of threshold is meaningful. This is due to the fact that we can expect the improvement factor to increase with RF bandwidth as shown by Equation C-1 for PCM and Equation C-3 for FM. However, it is important to recognize that as bandwidth is increased and more noise appears, the threshold also increases. We can therefore expect an optimum system improvement at threshold.

Combining Equations C-3 and C-4b we have the output signal-to-noise in terms of the overall input signal-to-noise

$$(S/N)_o = (3M^2 + 3M^3)\ (S/N)_{in} \qquad \text{C-5}$$

From Equation C-5 the modulation factor which will give the desired output signal-to-noise in terms of the threshold ratio can be determined. For high quality pictures the necessary output signal-to-noise ratio is in the neighborhood of 40 db. Solving Equation C-5 for $(S/N)_o$ = 40 db or a ratio of 10^4 and $(S/N)_{in}$ = 12 db or a ratio of 15.8 gives M = 5.6. From Equation C-4 the RF bandwidth for a baseband b of 4 Mc/s is 52.8 Mc/s and the actual improvement over $(S/N)_{RFb}$ is a ratio of 40.5 or 16.6 db.

In a PCM system the number of pulses per sample must be seven or greater in order that the quantization noise ratio, Q, be above 10^4 (equivalent to 40 db). From Equation C-1, Q = 2.4 X 10^4 or equivalent to 43.8 db for n = 7. For a television signal which is 4 Mc/s wide, this gives an RF bandwidth of 28 Mc/s for a SSB system.

The improvement at threshold is given by Equation C-2. However a minimum value of 14 db must exist to achieve this improvement. For $(S/N)_{p.d}$ of 14 db or a ratio of 25, $(S/N)_o$ equals a ratio of 10^5 or 50 db. The limitation on bandwidth of the PCM system is therefore dictated by the quantization noise and not the noise seen by the receiver at threshold.

If we now assume a constant noise power spectral density for both systems, we can determine the relative satellite ERP required at threshold. This is given by

$$\frac{P_T(PCM)}{P_T\ (FM)} = 1.6\ \frac{B(PCM)}{B(FM)} = 1.6\ \frac{28}{52.8} = .848 \qquad \text{C-6}$$

where 1.6 takes account of the fact that for PCM the minimum threshold must be 14 db or 2 db higher than the minimum value of 12 db for the FM cost. The power required by the PCM system is .71 db below that for the FM system, for the required minimum output signal-to-noise of 40 db. However, as was stated in the main body of this report, FM produces a triangular output noise which has less degradation effect than normal flat noise. For this reason, FM will have a lower power requirement at threshold than PCM to achieve an effective 40 db output quality referenced to noise in an AM (or SSB) system. It should be realized that the assumed 40 db required for high quality reception is based upon AM noise.

From the above, it appears that the main advantage in a PCM system is its conservation of bandwidth. However, it is costly due to the requirement for a seven bit decoder at the receiver; it has little flexibility since a seven bit code must be used; and does not provide a power reduction over an FM system which is operated in the vicinity of threshold.

APPENDIX D

TELEVISION STANDARDS

D-1 GENERAL

According to the recommendations of the TASO Committee, television broadcast standards should be designed in such a way as to provide the viewer with a high quality signal for a large percentage of the time. These recommendations were predicated on statistics on the subjective quality of pictures. In addition, the FCC has derived a series of curves which can be used to predict coverage as a function of frequency, power, and antenna height above ground. These serve as a basis for predicting a certain quality of signal from a particular station within defined contours of coverage. Signal qualities are referred to as Principal City, A, and B grades, and are identified with the presence of a certain field strength at not less than 50 per cent of the receiving stations within the particular coverage contour. The classes of service used to identify television coverage in the United States are summarized in Table D-1.

TABLE D-1

FCC FIELD STRENGTH REQUIREMENTS FOR TELEVISION GRADES OF SERVICE

Grade of Service	Quality Description	Required Signal Strength (Median Value)		
		Chs. 2-6	Chs. 7-13	Chs. 14-83
Principal City	Not explicitly defined	5010 μv/m	7080 μv/m	10,000 μv/m
A	Quality acceptable to a median observer which is available 90 per cent of the time at the best 70 per cent of receiver locations at the outer limits of the service area.	2510	3550	5010
B	Quality acceptable to a median observer which is available 90 per cent of the time at the best 50 per cent of receiver locations at the outer limits of the service area.	224	631	1580

The required signal strengths shown in Table D-1 are those specified by the FCC to be used for calculating the different grades of service for conventional television using ground-based transmitters. A close correlation with these values has been established from detailed studies of empirical data conducted by TASO and collected in the New York UHF-TV project. The pertinent results of these studies are tabulated in Table D-2.

TABLE D-2

MEASURED FIELD STRENGTH REQUIREMENTS FOR SPECIFIC GRADE OF SIGNAL AS DEFINED BY $(S/N)_o$

Signal Grade	Description	Median Observer S/N (db)	Median Field Strength (μv/m)		
			Chs. 2-6	Chs. 7-13	Chs. 14-83
1	Excellent; picture of extremely high quality	44.5	NA	NA	NA
2	Fine; high quality; Interference perceptible	33.5	1,000	5,400	10-33,000
3	Passable; acceptable quality; interference not objectionable	27	100	500	1,750
4	Marginal; poor quality; interference somewhat objectionable	23	25	100	500
5	Interior; very poor quality; objectionable interference present	17	--	31	175
6.	Unuseable;so bad could not watch it	--	--	13	60

D-2 STANDARDS OF QUALITY APPLICABLE TO SATELLITE SYSTEMS

Standards and experience with conventional ground-based television have relevance to the study in that they provide insight into the value of output signal to noise ratio required to provide different qualities of pictures. These values are shown in Table D-2 above and indicate a subjective determination using an average viewer. While much experience has been gained with respect to the field strength necessary to ascertain different qualities of reception from ground-based television stations, it is important to recognize that there is a significant difference between the effects on propagation from a ground-based transmitter to ground-based receivers as compared with propagation from a satellite to ground-based receivers. In the case of a ground-based system, it is necessary to specify received signal requirements in terms of a median field strength value. This takes into account the statistical variation in the value of received field strength. The statistical variations represent differences in received field strength with location and time from a median value. This variation is in the order of $\pm$ 10 db, and is caused by the fact that propagation is in the atmosphere and usually over rough terrain with receiving stations often shielded by terrain or man-made obstacles. It is to overcome this variation and provide for reception at a high percentage of locations for a high percentage of time that large values of median field strength are specified as requirements in Table D-2.

It is realistic to relate signal to noise output values with qualitites of service as shown in Table D-2 and apply these as requirements that are appropriate for reception from satellites. However, it is not realistic to use the values identified with ground-based television broadcasting as shown in Table D-2 as field strength requirements for satellite reception. The concept of a statistical distribution of received signal strength does not apply. A more meaningful method of determining signal strength requirements for reception from satellites is to relate the required signal to noise ratio at the receiver output to required signal and signal to noise at the input taking into account antenna gain, receiver noise figure, modulation improvement, frequency of operation, etc. This will establish the required signal strength from the satellite. From this the effective radiated power from the satellite can be calculated using the one-way propagation equation.

These factors are the ones considered in this study. For purposes of comparative analysis of the costs of various system combinations it is sufficient to consider that those combinations of factors which provide a S/N ratio equal to or greater than 35 db at the input of the receiver will provide a high quality picture; 40 db is used for purposes of this study as representing a good objective. It should be pointed out that a "per cent of the time" expression for received signal strength is eliminated by virtue of the relatively constant nature of the received signal.

A primary factor which will determine the amount of field strength required to provide a 40 db S/N at the receiver output is the amount of so-called "indigenous" noise at the receiving site. In other words, the amount of field strength required in rural areas, where there is little of this noise will be less than the field strength required in urbanized areas, where there is a high noise level. As indicated in other sections of this study, knowledge of present levels of indigenous noise is very scarce and present estimates must be based on rough approximations.

This section on television standards is based on the transmission and reception of a television signal using amplitude modulation. As indicated in Appendix C on modulation improvement, the use of other modulation techniques, e.g., FM and PCM, will permit the reduction in the required S/N at the input of the receiver to obtain a particular grade of signal. This correspondence between required S/N and modulation method is discussed in sufficient detail in that section and shall not be discussed further here, other than to note that specification of S/N is the preferred way of comparing and evaluating picture quality.

D-3 FREQUENCY BANDS

Table 3-D identifies the allocations to Broadcasting and Communications Services in the band .1-12 Gc/s. This study has not been concerned with the type of service under which satellite transmission of television might be accomplished--but rather has examined the technical factors that are applicable if it is assumed that this transmission might occur anyplace within the band .1-12 Gc/s.

D-4 INTERNATIONAL IMPLICATIONS

These discussions have been based on the television industry in the United States, where there is a well developed set of standards and practices based on the 525 line per picture system utilizing a channel width of 6 Mc/s, and a video bandwidth of 4 Mc/s. There are basically three other types of systems presently being used throughout the world. The pertinent characteristics of these four systems are summarized in Table D-4.

Because of the technical differences, the minimum requirement for S/N will vary somewhat between systems.

TABLE D-3

ALLOCATIONS TO BROADCASTING AND COMMUNICATIONS SERVICES

(.1-12 Gc/s)

Frequency Band (Mc/s)	Allocation	
	U.S.	International
100-108	Broadcasting	FM Broadcasting
174-216	Fixed, Mobile Broadcasting	TV Broadcasting
470-890	Broadcasting	TV Broadcasting
1710-1850	Fixed, Mobile	Unspecified Government
3500-3700	Fixed, Mobile Radio location; Comsat	Unspecified Government
3700-4200	Same as above	Common Carrier, Fixed Space
4400-4700	Same as above	Government Unspecified
5925-6425	Same as above	Common Carrier Fixed
7250-7300	Comsat	Comsat (Space)
7300-7750	Fixed, Mobile Comsat	Comsat, Metsat. (Space)
7900-7975	Same as above	Comsat (Earth)
7975-8025	Comsat	Comsat (Earth)
8025-8400	Fixed, Mobile, Comsat	Fixed, Mobile, Comsat (Earth)
11,700-12,700	Fixed, Mobile, Broadcasting	Common Carrier, TVSTV, and Pick up

TABLE D-4

WORLD TELEVISION STANDARDS

Characteristic	A	B	C	D
Number lines per picture	405	525	625	819
Video Bandwidth (Mc/s)	3	4	5	10.4
Channelwidth (Mc/s)	5	6	7	14
Interlace	211	211	211	211
Line Frequency (c/s)	10.125	15.750	15.625	20.475
Field Frequency (c/s)	50	60	50	60
Picture Frequency	25	30	25	25
Sound Modulation	AM	FM	FM	FM